PB-219 668

PHYSICAL-CHEMICAL TREATMENT OF COMBINED AND MUNICIPAL SEWAGE

Alan J. Shuckrow, et al

Battelle-Northwest

Prepared for:

Environmental Protection Agency

February 1973

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

W73-08127

PB 219 668

EPA-R2-73-149
February 1973

Environmental Protection Technology Series

Physical - Chemical Treatment of Combined and Municipal Sewage

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

Office of Research and Monitoring
U.S. Environmental Protection Agency
Washington, D.C. 20460

186

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Monitoring, Environmental Protection Agency, have been grouped into five series. These five broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and a maximum interface in related fields. The five series are:

1. Environmental Health Effects Research
2. Environmental Protection Technology
3. Ecological Research
4. Environmental Monitoring
5. Socioeconomic Environmental Studies

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

/

SELECTED WATER RESOURCES ABSTRACTS

INPUT TRANSAC TION FORM

1. Report No.

2.

3. Accession No.
W73-08127

4. Title Physical-Chemical Treatment of Combined and Municipal Sewage, (all caps)

5. Report Date

6. ~~November, 1972~~

8. Performing Organization Report No.

7. Author(s) Shuckrow, Alan J., Dawson, Gaynor W., and Bonner, William F.

10. Project No. EPA Project 11020 DSQ

9. Organization Battelle-
Pacific Northwest Laboratories
Richland, Washington. ~~99352~~

11. Contract/Grant No.
14-12-519

13. Type of Report and Period Covered

~~*12. Sponsoring Organization* EPA, Office of Research & Monitoring~~

15. Supplementary Notes
Environmental Protection Agency Technology Series report ~~number~~, EPA-R2-73-149, February 1973. 178 p, 88 fig, 31 tab, 14 ref, append.

16. Abstract
The research program included laboratory process development of a unique physical-chemical wastewater treatment process followed by design, construction, and field demonstration of a 100,000 gpd mobile pilot plant. In the treatment process, raw wastewater is contacted with powdered carbon, coagulated with alum, settled with polyelectrolyte addition and, in some cases, passed through a tri-media filter. The solids from the clarifier, composed of raw sewage solids, powdered carbon, and aluminum hydroxide floc, are readily dewaterable to 20-25 percent solids by direct centrifugation with the powdered carbon acting as a substantial aid to dewatering. The dewatered solids are passed through a fluidized bed furnace developed specifically for powdered carbon regeneration. Alum is recovered by acidifying the regenerated carbon slurry from the furnace to a pH of 2. The recovered carbon and alum are recycled as an acidified slurry and added to the raw sewage with the makeup carbon. The program demonstrated the ability of the treatment process to consistently produce high-quality effluent from raw wastewater. Powdered carbon regeneration was highly successful on the pilot scale. Full capacity recovery was achieved with less than two percent carbon loss per regeneration cycle. Alum recovery was also greater than ninety percent. (CPA)

17a. Descriptors
*Activated Carbon, *Adsorption, *Waste Water Treatment, *Pilot plants, ~~*Recycling~~, Alum, Coagulation, Polyelectrolytes, Filtration, Dewatering, Sewage treatment

17b. Identifiers
*Combined Sewage, Alum recovery, Carbon recovery

Copy available from GPO Sup Doc
as EP1.23/2:73-149, $2.35; microfiche
from NTIS as PB [illegible], $0.95.

17c. COWRR Field & Group

18. Availability

19. Security Class. (Report)

20. Security Class. (Page)

21. No. of Pages 178

22. Price

Send To:
WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

Abstractor Alan J. Shuckrow

Institution Battelle, Pacific Northwest Laboratories

WRSIC 102 (REV. JUNE 1971)

GPO 913.261

EPA-R2-73-149
February 1973

PHYSICAL - CHEMICAL TREATMENT
of
COMBINED and MUNICIPAL SEWAGE

by

Alan J. Shuckrow
Gaynor W. Dawson
William F. Bonner

Contract 14-12-519
Project No. 11020 DSQ

Project Officer
Mr. Danforth G. Bodien
Environmental Protection Agency
Seattle, Washington 98901

prepared for the

Office of Research and Monitoring
ENVIRONMENTAL PROTECTION AGENCY
Washington, D.C. 20460

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402
Price $2.35 domestic postpaid or $2 GPO Bookstore

EPA Review Notice

This report has been reviewed by the Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

ABSTRACT

A unique physical-chemical wastewater treatment system utilizing powdered activated carbon was developed and demonstrated by Battelle-Northwest under contract to the EPA. The research program included laboratory process development followed by design, construction, and field demonstration of a 100,000 gpd mobile pilot plant.

In the treatment process, raw wastewater is contacted with powdered carbon, coagulated with alum, settled with polyelectrolyte addition and, in some cases, passed through a tri-media filter. The solids from the clarifier, composed of raw sewage solids, powdered carbon, and aluminum hydroxide floc, are readily dewaterable to 20-25 percent solids by direct centrifugation with the powdered carbon acting as a substantial aid to dewatering. The dewatered solids are passed through a fluidized bed furnace developed specifically for powdered carbon regeneration. Alum is recovered by acidifying the regenerated carbon slurry from the furnace to a pH of 2. The recovered carbon and alum are recycled as an acidified slurry and added to the raw sewage with the makeup carbon.

The program demonstrated the ability of the treatment process to consistently produce high-quality effluent from raw wastewater.

Powdered carbon regeneration was highly successful on the pilot scale. Full capacity recovery was achieved with less than two percent carbon loss per regeneration cycle. Alum recovery was also greater than ninety percent.

Initial cost estimates, including both operation and capital amortization, are 16.8¢/1000 gal. for combined sewage treatment and 22-23¢/1000 gal. for raw municipal wastewater.

This report was submitted in fulfillment of Project # 11020 DSQ and Contract # 14-12-519 under the sponsorship of the U. S. Environmental Protection Agency.

CONTENTS

SECTION		PAGE
I	CONCLUSIONS	1
II	RECOMMENDATIONS	7
III	INTRODUCTION	9
IV	PILOT PLANT DESCRIPTION	15
V	DEMONSTRATION SITE	25
VI	TREATMENT SYSTEM PERFORMANCE	33
VII	REGENERATION	99
VIII	DESIGN AND ECONOMIC CONSIDERATIONS	133
IX	ACKNOWLEDGMENTS	141
X	REFERENCES	143
XI	APPENDIX A	145

FIGURES

NO.		PAGE
1	PROCESS FLOW SHEET	11
2	MOBILE PILOT PLANT	12
3	SCHEMATIC FLOWSHEET OF MOBILE PILOT PLANT	16
4	CHEMICAL INJECTION POINT IN PIPE REACTOR	17
5	FLUIDIZED BED REGENERATION UNIT	19
6	REGENERATION SYSTEM SCHEMATIC FLOWSHEET	21
7	PILOT PLANT IN OPERATION AT ALBANY SITE	22
8	FLUIDIZED BED CONTROL PANEL	23
9	ISLAND CREEK DRAINAGE AREA AND DEMONSTRATION SITE LOCATION	26
10	TYPICAL DIURNAL DRY WEATHER FLOW VARIATION AT ALBANY SITE	27
11	AVERAGE DIURNAL BOD AND COD FLUCTUATION AT ALBANY SITE	29
12	AVERAGE DIURNAL SUSPENDED SOLIDS AND TURBIDITY FLUCTUATION AT ALBANY SITE	30
13	AVERAGE DIURNAL PHOSPHATE FLUCTUATIONS AT ALBANY SITE	31
14	STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 7/13/71	38
15	STORM EFFECT ON COD - 7/13/71	39
16	STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 7/19/71	40
17	STORM EFFECT ON COD - 7/19/71	41
18	STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 7/29/71	42
19	STORM EFFECT ON SETTLEABLE SOLIDS - 7/29/71	43
20	STORM EFFECT ON BOD AND COD - 7/29/71	44

(FIGURES Continued)

21 STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 9/13-14/71 45

22 STORM EFFECT ON BOD AND COD - 9/13-14/71 46

23 STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 9/16-17/71 47

24 STORM EFFECT ON BOD AND COD - 9/16-17/71 48

25 STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/2/72 49

26 STORM EFFECT ON BOD AND COD - 5/2/72 50

27 STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/16/72 51

28 STORM EFFECT ON COD AND BOD - 5/16/72 52

29 STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/16/72 53

30 STORM EFFECT ON COD AND BOD - 5/16/72 54

31 STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/16-17/72 55

32 STORM EFFECT ON COD AND BOD - 5/16-17/72 56

33 JAR TEST DETERMINATION OF CARBON REQUIREMENTS DURING INCREASING AND PEAK LOADING OF 7/29/71 STORM 58

34 JAR TEST DETERMINATION OF CARBON REQUIRE- DURING DECREASING AND MINIMUM LOADING OF 7/29/71 STORM 59

35 PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 7/12-13/71 64

36 PLANT COD REMOVAL - 7/12-13/71 65

37 PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 7/14-15/71 66

38 PLANT COD REMOVAL - 7/14-15/71 67

39 PLANT COD AND BOD REMOVAL - 8/17-18/71 68

40 PLANT COD AND BOD REMOVAL - 9/28-29/71 69

(FIGURES Continued)

41 PLANT SUSPENDED SOLIDS REMOVAL - 10/4-5/71 70

42 PLANT COD AND BOD REMOVAL - 10/4-5/71 71

43 PLANT SUSPENDED SOLIDS REMOVAL - 10/7-8/71 72

44 PLANT COD AND BOD REMOVAL - 10/7-8/71 73

45 PLANT SUSPENDED SOLIDS REMOVAL - 10/13-14/71 74

46 PLANT COD AND BOD REMOVAL - 10/13-14/71 75

47 PLANT COD AND BOD REMOVAL - 10/25-26/71 76

48 PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 4/14 & 4/17-19/72 78

49 PLANT COD AND BOD REMOVAL - 4/14 & 4/17-19/72 79

50 PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 4/24-26/72 80

51 PLANT COD AND BOD REMOVAL - 4/24-26/72 81

52 PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 5/1-3/72 & 5/9-10/72 82

53 PLANT COD AND BOD REMOVAL - 5/1-3/72 & 5/9-10/72 83

54 PLANT TURBIDITY AND SUSPENDED SOLIDS REMOVAL - 5/16-17/72 & 5/23/72 84

55 PLANT COD AND BOD REMOVAL - 5/16-17/72 & 5/23/72 85

56 PLANT TURBIDITY AND SUSPENDED SOLIDS REMOVAL - 6/7-8/72 & 6/12/72 86

57 PLANT COD AND BOD REMOVAL - 6/7-8/72 & 6/12/72 87

58 PLANT TURBIDITY AND SUSPENDED SOLIDS REMOVAL - 6/13-15/72 88

59 PLANT COD AND BOD REMOVAL - 6/13-15/72 89

60 FREQUENCY DISTRIBUTION OF PILOT PLANT EFFLUENT QUALITY 90

(FIGURES Continued)

61	CUMULATIVE PROBABILITY DISTRIBUTION OF ACHIEVING REMOVAL PERCENTAGES GREATER THAN OR EQUAL TO A GIVEN VALUE	91
62	CHLORINE DEMAND OF PLANT EFFLUENT	95
63	LIME USAGE DURING REGENERATION STUDIES	96
64	IRON INVENTORY IN REGENERATED CARBON SLURRY	107
65	INERTS BUILDUP IN REGENERATED CARBON	109
66	JAR TESTS ON ONCE REGENERATED CARBON - BATCH A	112
67	JAR TESTS ON TWICE REGENERATED CARBON - BATCH A	113
68	JAR TESTS ON THREE TIMES REGENERATED CARBON - BATCH A	114
69	JAR TESTS ON FOUR TIMES REGENERATED CARBON - BATCH A	115
70	JAR TESTS ON ONCE AND TWICE REGENERATED CARBON - BATCH C	116
71	JAR TESTS ON THREE TIMES REGENERATED CARBON - BATCH C	117
72	JAR TESTS ON FOUR TIMES REGENERATED CARBON - BATCH C	118
73	JAR TESTS ON FIVE AND SIX TIMES REGENERATED CARBON - BATCH C	119
74	JAR TESTS ON SEVEN TIMES REGENERATED CARBON - BATCH C	120
75	ALUMINUM BUILDUP IN REGENERATED CARBON	123
76	ACID USAGE DURING REGENERATION STUDIES	124
77	EFFECT OF BLOWDOWN RATE ON TREATMENT COSTS FOR A 10 MGD PLANT	132

TABLES

NO.		PAGE
1	DIURNAL WASTEWATER CHARACTERISTICS AT ALBANY SITE DURING DRY WEATHER	28
2	AVERAGE WASTEWATER CHARACTERISTICS AT ALBANY SITE DURING 1971 PILOT OPERATIONS	32
3	OPERATIONAL DATA DURING STORM FLOWS	37
4	PLANT OPERATIONAL DATA FOR 1971 STUDIES USING VIRGIN CARBON	61
5	PLANT OPERATIONAL DATA FOR DIURNAL STUDIES	62
6	PLANT PERFORMANCE DATA DURING 1971 OPERATIONS USING VIRGIN CARBON	63
7	PILOT PLANT PERFORMANCE AT LOW CARBON DOSES	93
8	REGENERATED CARBON PERFORMANCE COMPARISON	98
9	FLUIDIZED BED-FURNACE OPERATING CONDITIONS	102
10	SIEVE ANALYSES OF FLUIDIZED BED SAND	105
11	ALUMINUM MASS BALANCE SUMMARY	122
12	STACK SAMPLING DATA	126
13	CARBON MASS BALANCE SUMMARY	128
14	SIEVE ANALYSIS OF FLUIDIZED BED SAND COLLECTED WITH REGENERATED CARBON	130
15	SYSTEM DESIGN PARAMETERS	135
16	CAPITAL COST ESTIMATES FOR 10 MGD MUNICIPAL WASTEWATER AND STORM WATER TREATMENT PLANTS	136
17	SYSTEM OPERATING PARAMETERS	137
18	OPERATING COST ESTIMATES FOR 10 MGD MUNICIPAL WASTEWATER AND STORM WATER TREATMENT PLANTS	138
19	TOTAL COSTS FOR 10 MGD MUNICIPAL WASTEWATER AND STORM WATER TREATMENT PLANTS	139

SECTION XI

APPENDIX A

PAGE

LABORATORY STUDIES 145

GENERAL 145

CARBON STUDIES 145

TABLE A-1: COMPOSITION OF RICHLAND SEWAGE 146-147

FIGURE A-1: BENCH SCALE SYSTEM 148

FIGURE A-2: EFFECT OF CARBON CONCENTRATION ON EQUILIBRIUM COD 150

FIGURE A-3: EFFECT OF CARBON CONCENTRATION ON EQUILIBRIUM TOC 151

FIGURE A-4: EFFECT OF CONTACT TIME ON TOC REMOVAL 152

TABLE A-2: COMPARISON OF VARIOUS CARBONS - CONTACT TESTS 153

BENTONITE PROCESS DEVELOPMENT 154

TABLE A-3: COMPARISON OF VARIOUS CARBONS - JAR TESTS 155

FIGURE A-5: EFFECT OF BENTONITE CONCENTRATION ON EFFLUENT QUALITY 156

TABLE A-4: BENCH SCALE SYSTEM OPERATIONAL DATA - TUBE SETTLER 157

TABLE A-5: UPFLOW CLARIFIER OPERATING DATA 159

ALUM PROCESS PRELIMINARY INVESTIGATIONS 160

CARBON REGENERATION 160

FIGURE A-6: EFFECT OF ALUM DOES ON COD AND TURBIDITY REMOVAL 161

TABLE A-6: UPFLOW CLARIFIER SYSTEM - ALUM PROCESS PERFORMANCE 162

(APPENDIX A Continued)

TABLE A-7: TUBE SETTLER SYSTEM - ALUM PROCESS 163

TABLE A-8: ANALYSIS OF REGENERATED CARBON MIXTURES 165

ALUM RECOVERY 166

POLYELECTROLYTE SCREENING STUDY 166

FIGURE A-7: CAPACITY RECOVERY OF BATTELLE-COLUMBUS REGENERATED CARBON-ALUM PROCESS 167

FIGURE A-8: CAPACITY RECOVERY OF BATTELLE-COLUMBUS REGENERATED CARBON-BENTONITE PROCESS 168

FIGURE A-9: CAPACITY RECOVERY OF FMC REGENERATED CARBONS 169

TABLE A-9: JAR TEST RESULTS WITH REGENERATED CARBONS 170

FIGURE A-10: EFFECT OF pH ON ALUMINUM RECOVERY 171

FIGURE A-11: ACID REQUIREMENT VERSUS pH-BCL CARBON-ALUM MIXTURE 172

TABLE A-10: FLOCCULATION PERFORMANCE OF VARIOUS POLYELECTROLYTES 173

TABLE A-11: EFFECT OF DOSE ON POLYELECTROLYTE PERFORMANCE - ALUM SYSTEM 174

ALUM PROCESS OPTIMIZATION 175

TABLE A-12: EFFECT OF POLYELECTROLYTE DOSE ON BENCH SCALE PERFORMANCE 176

SECTION I

CONCLUSIONS

A physical-chemical process utilizing powdered activated carbon for the treatment of sanitary and combined sewage has been successfully demonstrated on the 100,000 gal/day scale at Albany, New York. Carbon regeneration in a fluidized bed furnace and alum recovery from the calcined sludge have also been demonstrated as has been reuse of the reclaimed chemicals. This demonstration project has established the technical and economic feasibility of the process for both sanitary and combined sewage treatment. On the basis of laboratory studies and the pilot plant demonstration, the major conclusions listed below were drawn.

LIQUID TREATMENT PROCESS

- A process using powdered activated carbon, alum and a high molecular weight anionic polymer is highly effective in treating both sanitary and combined sewage.
- A carbon contact time of 5-10 minutes prior to hydrous aluminum oxide precipitation is required in order to insure consistently high treatment efficiency.
- A total carbon contact time of less than 15 minutes is required for equilibrium removal of sorbable organics.
- The carbon dose can be adjusted to effect the degree of sorbable organic removal required.
- A residual, nonadsorbable fraction ranging from 10-20 mg/l BOD and 20-50 mg/l COD existed at times in the Albany sewage. This fraction could not be removed at activated carbon doses as high as 1000 mg/l.
- A carbon dose of 500-600 mg/l was required to produce a high quality effluent from the municipal sewage treated.
- It was possible to reduce the carbon dose to 200 mg/l during the nighttime hours at the Albany site without affecting effluent quality. Decreasing the

carbon dose in this manner during that portion of the day when the sewage has a low soluble organic content can greatly reduce operating costs without sacrificing treatment efficiency.

- An average carbon dose of 500 mg/l achieved tertiary levels of treatment in the case of combined sewage during pilot operations. Jar test data indicate that the required carbon dose to achieve these levels is less than 400 mg/l.
- Alum [$Al_2(SO_4)_3 \cdot 18H_2O$] and polyelectrolyte requirements were 200 mg/l and 2.0 mg/l, respectively for both sanitary and combined sewage treatment.
- Lime [$Ca(OH)_2$] requirements when reclaimed alum was used in the treatment process averaged 190 mg/l during the Albany, New York demonstration. It should be possible to reduce the lime requirement to 150 mg/l or less in an actual operating plant.
- Tube settling contributes to minimizing process detention time. However, conventional sedimentation can be employed in the system if a longer process detention time is acceptable.
- The tube settler operated effectively at a hydraulic loading of 2880 gpd/ft^2.
- Efficient filtration was accomplished at filter loading rates in excess of 4 gpm/ft^2.
- Filtration provides an added degree of reliability which is essential for a municipal waste treatment plant and therefore, should be included if the process is to be employed in this manner. On the other hand, if a system is designed to operate during periods of combined overflow only and a certain amount of solids carry-over in the effluent is acceptable, filtration may not be necessary.
- The powdered activated carbon treatment process can accommodate wide fluctuations in effluent composition.
- The treatment system lends itself to a high degree of automation.
- During periods of storm flows it should be possible to adjust chemical feed rates automatically on the basis of influent flow rate.

- Turbidity can be used as an index to predict changes in other influent parameters during periods of storm flows. Thus, it may be feasible to adjust the carbon dose during a storm on the basis of turbidity.
- Treatment of raw and combined sewage can be accomplished in a total time of 50 minutes or less. This short detention time leads to a small land area requirement for the treatment system.
- The powdered activated carbon treatment process described in this report is free of the hydrogen sulfide problem associated with physical-chemical systems utilizing granular activated carbon.
- The process can be operated on an intermittent basis with a negligible time requirement for startup if chemical feed stocks are maintained.
- The treatment process is highly reliable.
- Average removals in excess of 94 percent COD, 94 percent BOD, and 99 percent suspended solids were consistently achieved in treating combined sewage.
- Average BOD, COD, suspended solids and turbidity levels in the pilot plant effluent from the sanitary sewage treatment operations were 17 mg/l, 36 mg/l, 5 mg/l, and 0.6 JTU, respectively.
- In characterizing a waste stream or in shaking down a new plant, frequent sampling must be carried out in order to detect rapid fluctuations in waste stream composition.
- Physical-chemical treatment of raw municipal waste streams in some instances will produce tertiary levels of treatment while in others only secondary levels can be achieved. Each waste stream must be examined on a case-by-case basis to determine the level of BOD removal which can be achieved.

SLUDGE HANDLING

- Carbon sludge should represent 1-2 percent of the plant flow in a full-scale facility.

- A product containing 22 percent solids can be obtained from direct centrifugation of the carbon sludge.

- A conditioning polymer is required to achieve 95 percent capture in the centrifuge.

- The required conditioning polymer dose for fresh sludge is 1-2 lbs/ton dry solids. Sludge aged for 2-3 days required a conditioning polymer dose of up to 4 lbs/ton dry solids to achieve 95 percent capture in the centrifuge.

CARBON REGENERATION

- Powdered activated carbon can be successfully regenerated in a fluidized bed furnace.

- Satisfactory regeneration can be achieved at a temperature of 1250°F with a stack gas oxygen concentration of less than 0.5 percent.

- After 6.7 regenerations, the regenerated carbon is as effective as virgin carbon in removing organic matter from raw sewage.

- Average carbon losses per regeneration cycle were 9.7 percent.

- Hearth plugging problems during the pilot plant operations resulted from corrosion of the recycle gas system. Such corrosion problems can be precluded easily in design of a full scale system.

- A high initial buildup of inert materials in the regenerated carbon during the first cycle regenerations is believed to have resulted from causes external to the regeneration system. Installation of a grit chamber in the treatment system should guard against high fluctuations in inert material buildup in the regenerated product.

- Inert material buildup averaged 2.9 percent per cycle during the pilot plant operations.

- Sand carryover from the fluidized bed furnace is believed to represent the most significant fraction of this buildup.

- Minimum operating costs are achieved with a five percent blowdown of carbon and inerts.

- Classification of the carbon and inerts would result in less carbon lost to blowdown and thus a reduction in operating costs.

- Stack gases from the regeneration furnace should not present significant air pollution problems.

ALUM RECOVERY

- Approximately 91 percent of the aluminum can be recovered by acidification of the carbon-alumina slurry to pH 2 with sulfuric acid after thermal regeneration of the carbon sludge.

- Acidification of the carbon-alumina slurry dissolves inerts in addition to alumina. These dissolved solids are discharged in the plant effluent and thus the solids buildup in the reclaimed chemicals is reduced.

- Sulfuric acid requirements for alum recovery were 0.6 lbs H_2SO_4/lb of carbon for the pilot operations. A reduction to 0.5 lbs H_2SO_4/lb of carbon appears feasible.

SECTION II

RECOMMENDATIONS

- As a result of the successful laboratory studies and pilot plant demonstration, efforts should proceed toward a full-scale demonstration of the powdered activated carbon treatment process.
- The powdered carbon treatment process should be demonstrated on a large scale basis for treatment of both raw and combined sewage.
- Design parameters for conventional sedimentation should be developed.
- An effort should be initiated to define the upper limit of loading of the tube settler without solids carryover.
- The necessity of stack gas recycle should be examined since elimination of the stack gas recycle stream would reduce capital costs.
- A reliable and accurate analytical method for determining the spent carbon content of sludge should be developed.
- If the powdered activated carbon process is to be used as an advanced waste treatment process for the treatment of raw sewage, it would be desirable to develop a method to remove phosphorus from the reclaimed alum. This would provide the added dimension of phosphate removal in the treatment process.
- The composition of the nonadsorbable organic fraction should be determined and methods for its removal explored.
- An efficient classification method for separating sand from regenerated carbon should be identified to reduce total blowdown and carbon losses.
- Further investigation of the usefulness of turbidity as an index of solids and organic loadings during storms should be pursued with a view towards automation of carbon and chemical feed rates in response to turbidity monitoring signals.

Preceding page blank

INTRODUCTION

The problem posed by combined sewer overflows is well documented. In 1967, it was estimated that $48 billion would be required to eliminate these overflows by installing separate collection systems for sanitary wastes and storm water(1). This estimate did not include the monetary loss which would be experienced by commerce and industry as the streets through the centers of major cities were torn up for installation of the separated systems. In addition to economics, the possibility of separation of all sewers, particularly in areas of high population density, was remote. Even if complete separation were accomplished, this measure would not be entirely satisfactory since storm water runoff is, itself, often severely polluted, particularly in highly urbanized areas(2,3,4). In fact, the pollutional effect of surface drainage water can be so significant that it will, in many cases, be necessary to treat storm runoff before it is allowed to reach receiving waters(4).

Recognizing the tremendous problems associated with sewer separation, the Storm and Combined Sewer Pollution Control Branch of the Water Quality Office embarked on a program to seek alternatives to this measure. They estimated that the development of alternative means of treatment could conceivably reduce this cost by two-thirds.

Therefore, as part of the Water Quality Office program, Contract No. 14-12-519 was negotiated with Battelle-Northwest to develop, through laboratory experimentation and pilot plant demonstration, a novel physical-chemical process for treatment of combined storm and sanitary sewage.

The treatment process was developed with the following goals:

- The quality of the effluent should be comparable to that routinely discharged from a secondary sewage treatment plant.
- Short detention times are mandatory due to the high flow rates likely to be encountered and the undesirability of allocating large land areas for treatment of combined sewage.
- The process must be amenable to intermittent operation with a minimum time requirement for startup.

Preceding page blank

- Treatment of combined sewage by such a process must be economically feasible.

The developed process, as outlined in Figure 1, involves contacting raw or combined sewage with powdered activated carbon to effect removal of dissolved organic matter. An inorganic coagulant, alum, is then used to aid in subsequent clarification. Addition of polyelectrolyte is followed by a short flocculation period. Solids are separated from the liquid stream by gravity settling, and the effluent is then disinfected and discharged or can be filtered prior to disinfection.

Bench scale laboratory experiments and pilot studies indicated that a 30-45 minute overall detention time is required. A ten-minute contact time prior to flocculation is necessary for good organic removal. Floc with excellent settling characteristics is consistently produced. This, coupled with highly efficient tube settling, leads to the very short process detention time.

Carbon sludge from the treatment process is thermally regenerated by a fluidized bed process. Alum is recovered by acidifying the regenerated carbon-aluminum oxide mixture to pH 2 with sulfuric acid. This reclaimed alum is then reused in the treatment process. A pH adjustment, accomplished with a lime slurry, is required to raise the pH to 6.5-7.0 for aluminum hydroxide precipitation when reclaimed alum is recycled.

A nine-month laboratory study which is described in Appendix A and elsewhere(5) indicated that the process goals could be met. In addition, the laboratory phase of the program demonstrated that the treatment process could be highly effective for raw sewage. Consequently, a 100,000 gpd mobile treatment plant (Figure 2) was designed and constructed.

Following construction of the mobile pilot plant, it was operated for a one-month shakedown at Richland, Washington. After minor equipment alterations were made, the process performed as well or better than anticipated from the laboratory study. Although this operation at Richland was primarily for shakedown purposes, a limited amount of performance data was obtained. Treating raw municipal wastes, TOC removals averaged better than 90 percent while suspended solids removals averaged better than 95 percent. Product water turbidities were consistently below 2 JTU. The resultant sludges were dewatered to 20 percent solids in a continuous solid bowl centrifuge without any preconditioning or supplemental thickening.

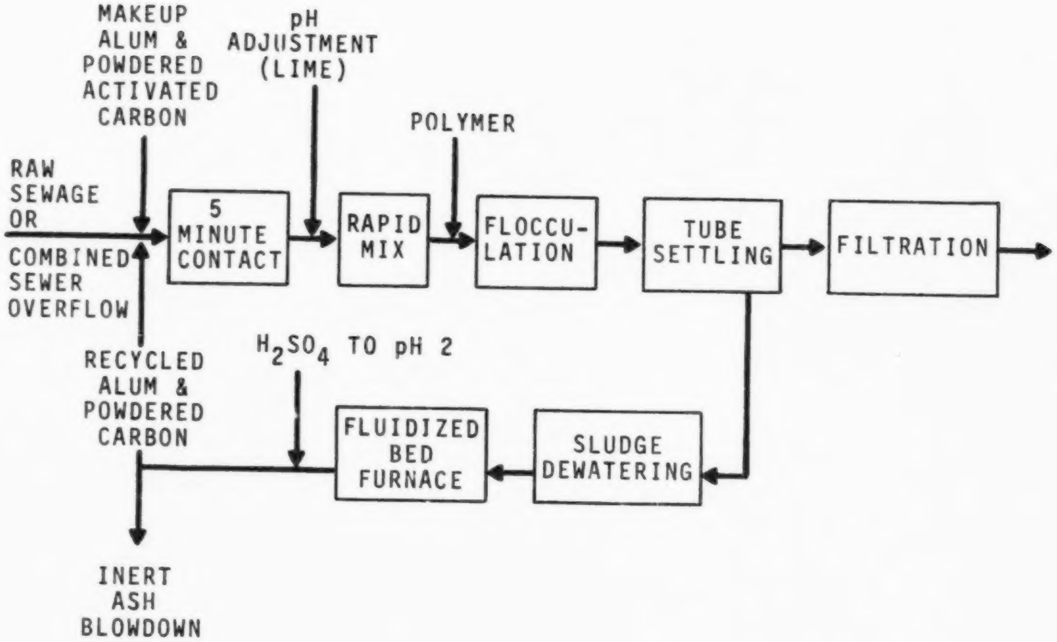

MAKEUP ALUM & POWDERED ACTIVATED CARBON
pH ADJUSTMENT (LIME)
POLYMER
RAW SEWAGE OR COMBINED SEWER OVERFLOW
5 MINUTE CONTACT
RAPID MIX
FLOCCU-LATION
TUBE SETTLING
FILTRATION
RECYCLED ALUM & POWDERED CARBON
H_2SO_4 TO pH 2
FLUIDIZED BED FURNACE
SLUDGE DEWATERING
INERT ASH BLOWDOWN

FIGURE 1. PROCESS FLOW SHEET

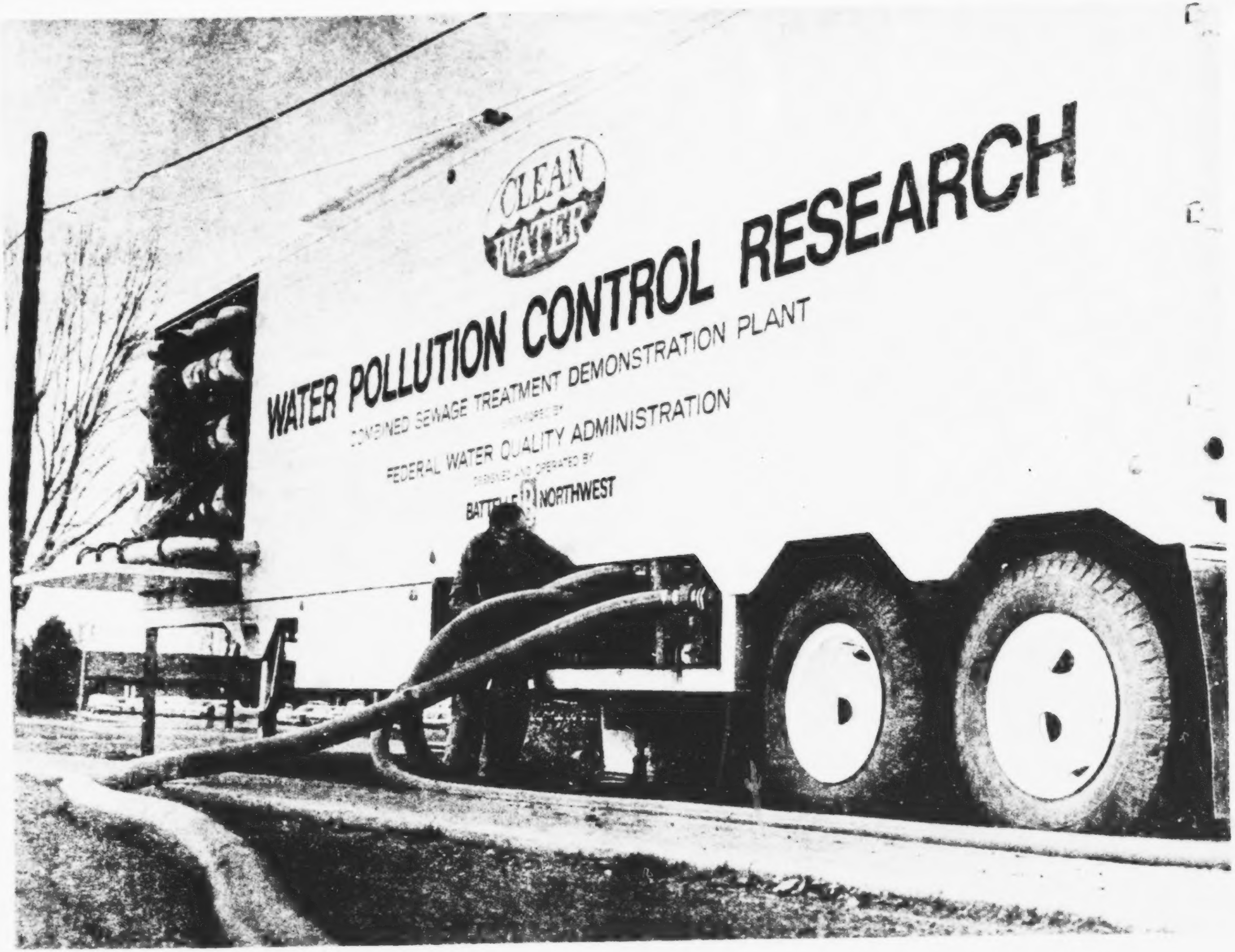

CLEAN WATER
WATER POLLUTION CONTROL RESEARCH
COMBINED SEWAGE TREATMENT DEMONSTRATION PLANT
SPONSORED BY
FEDERAL WATER QUALITY ADMINISTRATION
DESIGNED AND OPERATED BY
BATTELLE NORTHWEST

FIGURE 2. MOBILE PILOT PLANT

Upon completion of the shakedown operation, the mobile pilot plant was shipped to Albany, New York, where it was operated from mid-June through October 1971. Since the pilot plant was not designed for cold weather operation, it was shut down for the winter months. Operations were resumed in early April of 1972 and continued through the month of June of that year. This report describes the results of the pilot plant demonstration in Albany.

SECTION IV

PILOT PLANT DESCRIPTION

The pilot plant is composed of two major systems: a liquid treatment system and a carbon regeneration facility.

TREATMENT SYSTEM

The liquid treatment system is housed, almost entirely, in a forty-foot mobile trailer van. A schematic diagram of the process flowsheet is given in Figure 3. The major components are

- Surge Tank
- Pipe Reactor and Static Mixers
- Chemical Addition Equipment
- Flocculation Chambers
- Tube Settler
- Tri-media Filter
- Centrifuge

It is designed for a nominal capacity of 100,000 gal/day. Carbon, alum, and polyelectrolyte are added in a pipe reactor, providing rapid mixing of the chemicals, which preceeds flocculation followed by separation via a tube settler. Clarified effluent is chlorinated and released with the option of routing through a gravity filter prior to chlorination. Sludge is dewatered in the centrifuge.

The system is designed for maximum operational flexibility and includes turbidity, pH and flow monitoring instruments.

Sanitary or combined sewage is pumped from a sewer to a surge tank, screened and then pumped to a six-inch diameter stainless steel pipe reactor. The pipe reactor consists of 62 sections of 7'4" pipe arranged in an eight by eight array. The pipe centers are located at the apexes of equilateral triangles. This arrangement allows for one pipe elbow section to be connected at six locations while rotating through a 360° circle. Connections between straight pipe lengths and 180° returns are made with quick disconnect couplings.

The total pipe reactor length of 560 feet will allow a detention time of ten minutes at a flow rate of 75 gpm. Chemical feed connections are provided at various locations along the pipe reactor as illustrated in Figure 4 with

Preceding page blank

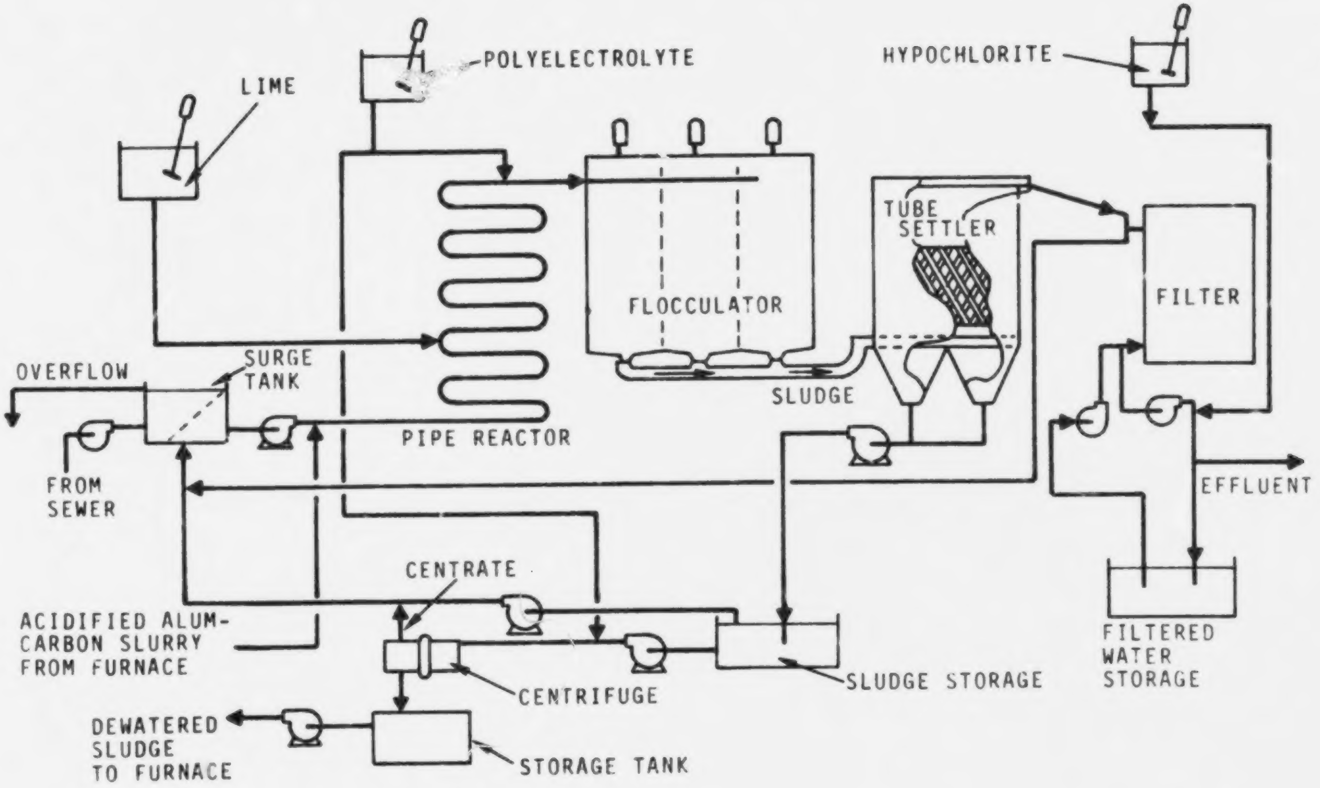

LIME
POLYELECTROLYTE
HYPOCHLORITE
TUBE SETTLER
FLOCCULATOR
FILTER
OVERFLOW
SURGE TANK
SLUDGE
FROM SEWER
PIPE REACTOR
EFFLUENT
CENTRATE
ACIDIFIED ALUM-CARBON SLURRY FROM FURNACE
CENTRIFUGE
SLUDGE STORAGE
FILTERED WATER STORAGE
DEWATERED SLUDGE TO FURNACE
STORAGE TANK

FIGURE 3. SCHEMATIC FLOWSHEET OF MOBILE PILOT PLANT

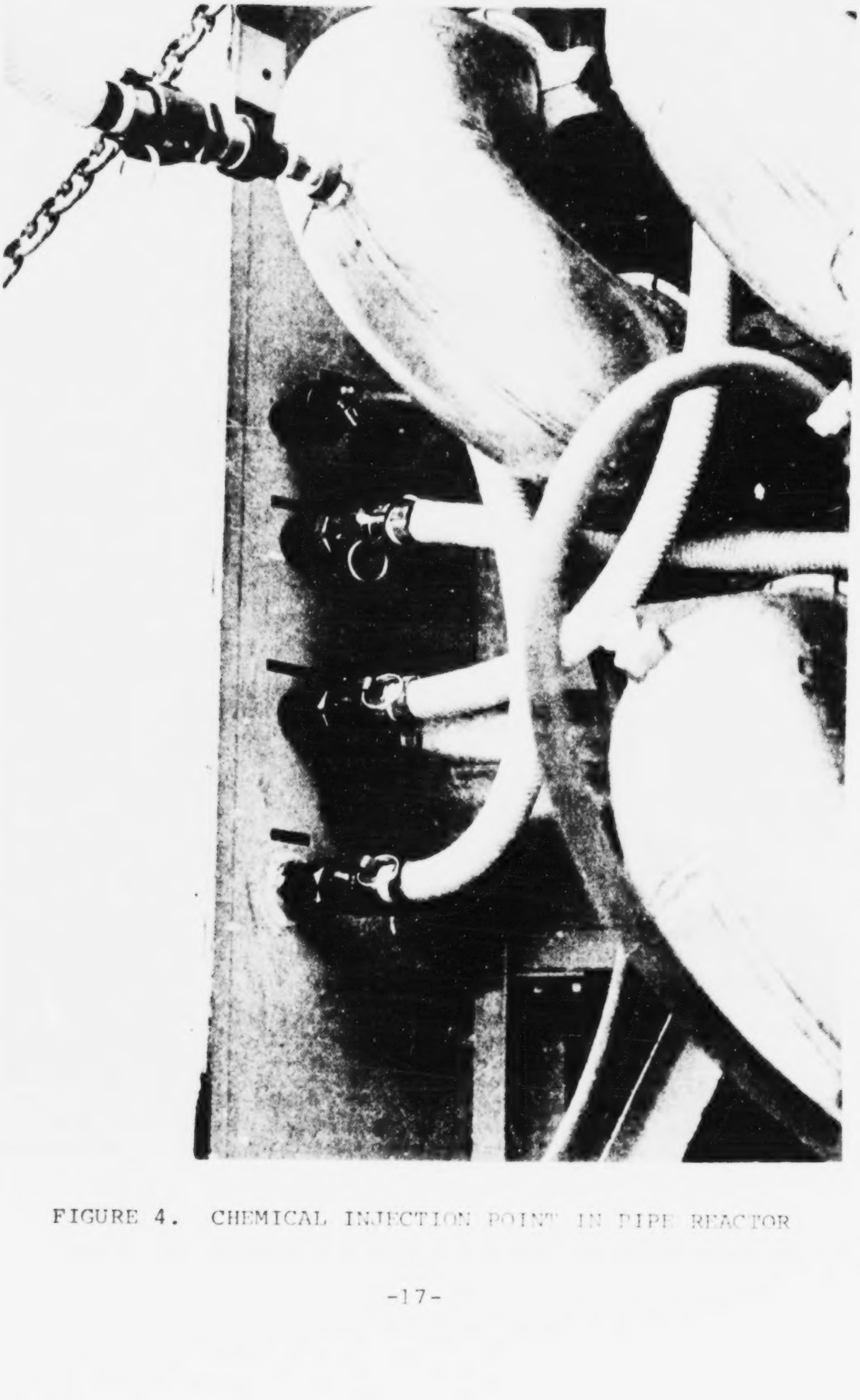


FIGURE 4. CHEMICAL INJECTION POINT IN PIPE REACTOR

helical static mixers located after each chemical injection point. These static mixers assure rapid, effective chemical mixing. Powdered activated carbon and alum are added at the head end of the pipe reactor, lime is added to adjust the pH approximately 280 feet downstream and finally, polyelectrolyte is added at the end of the pipe reactor.

After polyelectrolyte addition, the treated influent can be divided into one, two or three parallel streams. Each stream enters a 400 gallon flocculator. At 25 gpm per flocculator, nominal detention time is sixteen minutes.

Flocculator effluent leaves through a six-inch valve and enters the tube settler via an increasing cross-sectional area channel which keeps the flow velocity below one-foot per second to minimize break up of floc. The tube settler contains 25 sq. ft. of steeply (60°) inclined tubes. Separated sludge is pumped to a 3200 gallon storage tank prior to dewatering. Tube settler effluent can be chlorinated and discharged directly or can be filtered prior to disinfection. Filtration is accomplished in a 16 sq. ft. tri-media filter. The filter contains 5 in. of 40 x 80 mesh garnet sand, 9 in. of 20 x 40 mesh quartz sand, and 16.5 in. of 10 x 40 mesh anthrafilt.

A six-inch solid bowl centrifuge is used to dewater sludge which is then stored in a holding tank and subsequently pumped to the carbon regeneration facility. Centrate from the dewatering operation and filter backwash water are returned to the surge tank for recycle through the treatment system.

REGENERATION FACILITY

The fluidized inert sand bed unit of the regeneration facility is 36 in. I.D., refractory lined, and self supported. As illustrated in Figure 5, this unit consists of three main sections: a firebox housing the burner 30 in. I.D. x 20 in. high, a bed section containing inert sand 27 in. I.D. bottom, 36 in. I.D. top x 60 in. high and a freeboard 36 in. I.D. x 72 in. high.

Combustion of propane gas takes place in the firebox which is also the point of injection of recycling gases to maintain a 2,000°F atmosphere. The hot gases pass through vertical holes in a brick hearth fluidizing the inert sand bed. Carbon sludge at approximately 78 percent moisture is injected into the 1250°F turbulent bed where rapid heat transfer is obtained between gases and materials. The mixture of steam, combustion products, and regenerated

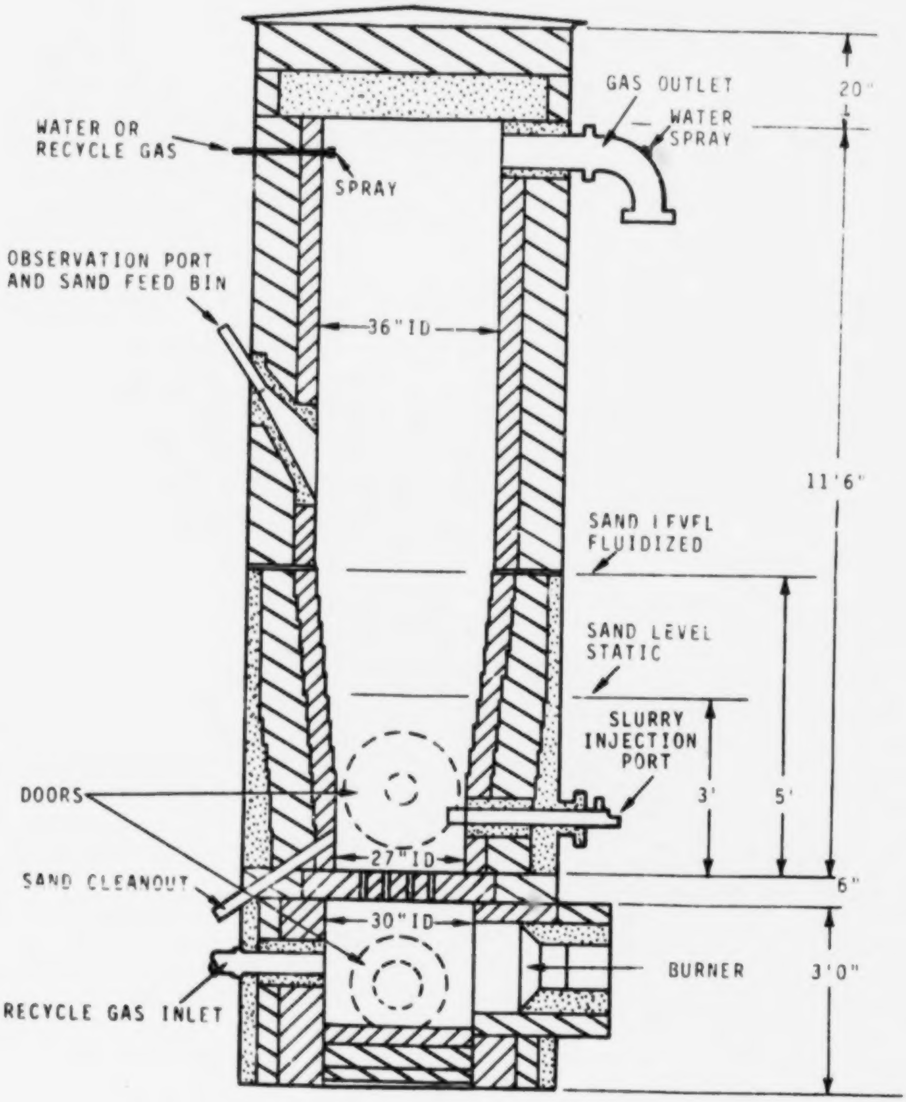

GAS OUTLET
WATER SPRAY
20"
WATER OR RECYCLE GAS
SPRAY
OBSERVATION PORT AND SAND FEED BIN
36"ID
11'6"
SAND LEVEL FLUIDIZED
SAND LEVEL STATIC
SLURRY INJECTION PORT
DOORS
3'
5'
27"ID
6"
SAND CLEANOUT
30"ID
BURNER
3'0"
RECYCLE GAS INLET

FIGURE 5. FLUIDIZED BED REGENERATION UNIT

carbon rises to the freeboard area and exits near the furnace top on the side at 1200°F to a venturi scrubber and cyclonic type separator. Exhaust gases at 150-200°F are vented to the atmosphere through a scrubber stack with a portion being recycled to the firebox. The regenerated carbon slurry from the scrubber is passed through a 60 mesh screen to remove large sand particles carried over from the fluidized bed. During the 1972 operation, a small settling chamber, three inches deep by one foot square, was installed ahead of the screen. Most of the larger sand particles were captured in this chamber, thus reducing the load on the screen and eliminating the need for frequent cleaning of the screen. After passing through the 60 mesh screen, the slurry was collected in storage tanks. Water for the venturi scrubber was continuously decanted from the storage tanks at 6-12 gpm and recirculated.

The fluidized bed is suitably lined to produce a maximum skin temperature of 150-200°F, while a bed temperature of approximately 1500°F is maintained. The shell itself is of steel construction. The whole system is pressurized (windbox, bed, freeboard) such that the summation of pressure drop through the fluidized bed and scrubbing system will be less than the pressure developed by the turbo-blowers. The fluidized bed is provided with necessary access port, observation port, sand inlet, sampling ports, sand clean-out, thermocouples, pressure tap connections, feed inlets and auxiliary propane gas gun.

Once furnace operation is begun, its control is automatic. Combustion air, recycle gas, propane and carbon sludge flow rates are initially set manually to achieve the desired temperatures, O_2 level, and bed velocity. Once set, the bed temperature is maintained automatically by varying the combustion air flowrate. (The propane flow changes proportionately with the combustion air flow to maintain a relatively constant O_2 level.)

After collection, the regenerated carbon slurry is acidified to pH 2 with sulfuric acid in order to reclaim the alum before reuse in the system.

A schematic diagram of the carbon regeneration system is presented in Figure 6. Figures 7 and 8 are two views of the regeneration furnace in place at the Albany site.

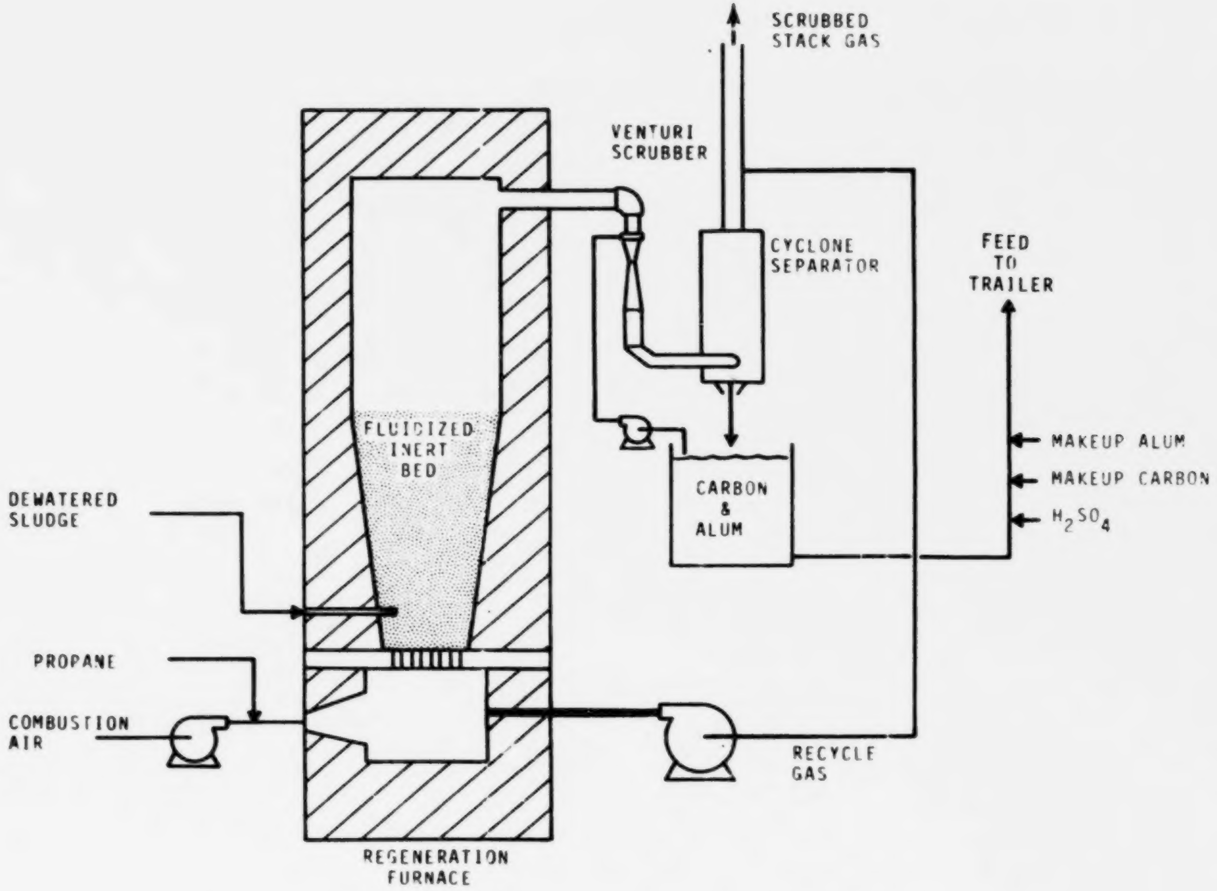
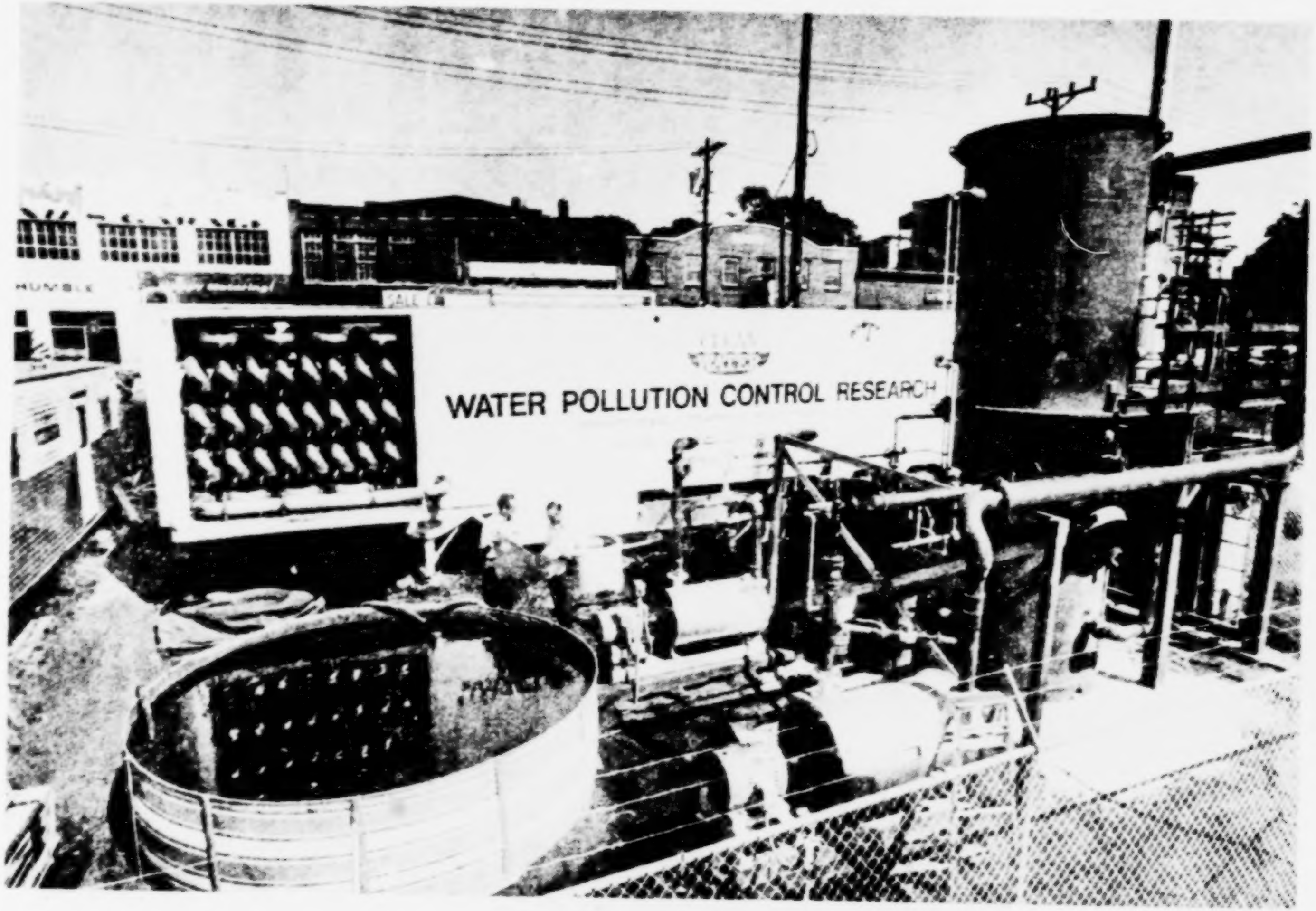
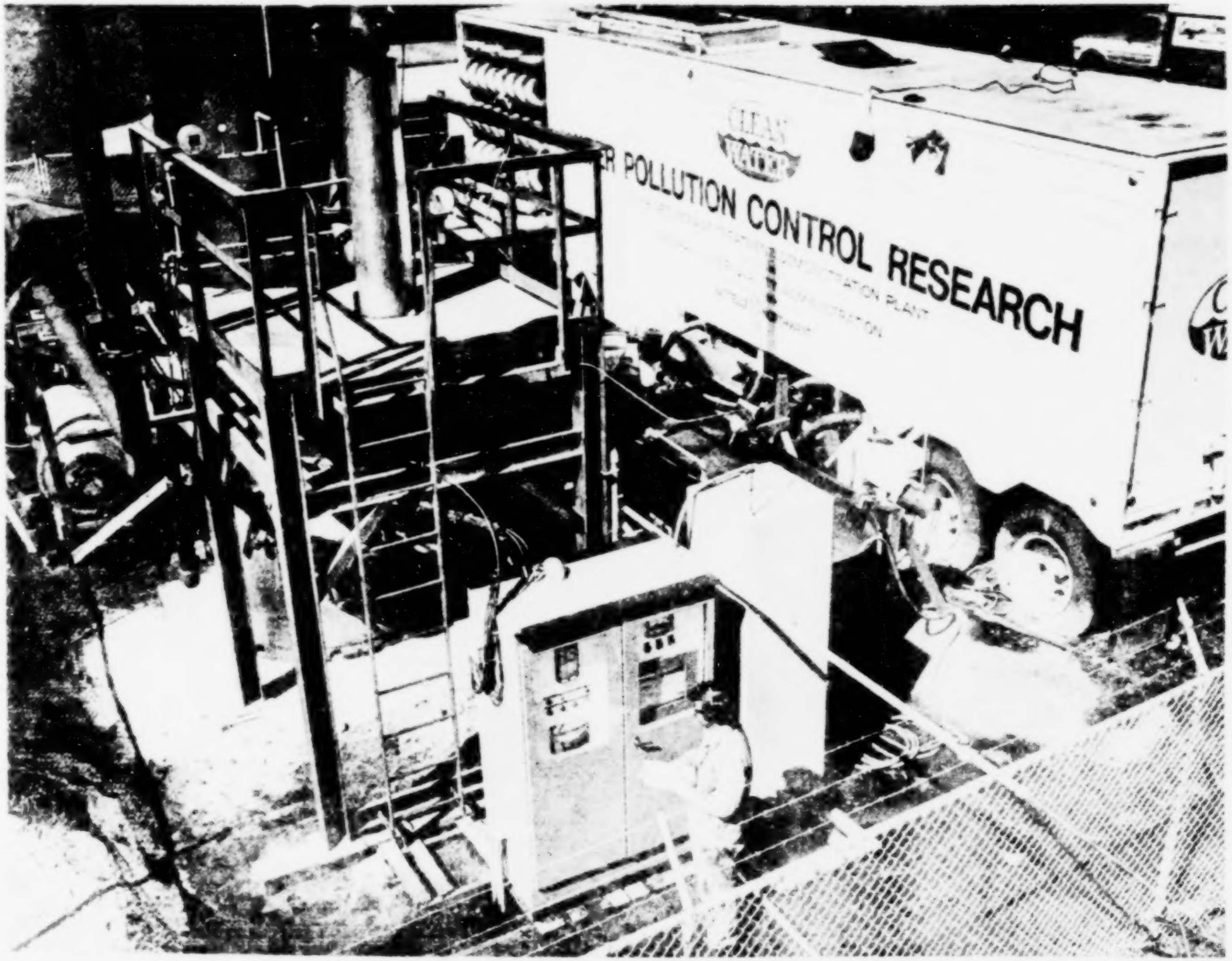

SCRUBBED
STACK GAS
VENTURI
SCRUBBER
CYCLONE
SEPARATOR
FEED
TO
TRAILER
FLUIDIZED
INERT
BED
MAKEUP ALUM
MAKEUP CARBON
H_2SO_4
CARBON
&
ALUM
DEWATERED
SLUDGE
PROPANE
COMBUSTION
AIR
RECYCLE
GAS
REGENERATION
FURNACE

FIGURE 6. REGENERATION SYSTEM SCHEMATIC FLOWSHEET



WATER POLLUTION CONTROL RESEARCH
HUMBLE

FIGURE 7. PILOT PLANT IN OPERATION AT ALBANY SITE



CLEAN WATER
R POLLUTION CONTROL RESEARCH
DEMONSTRATION PLANT

FIGURE 8. FLUIDIZED BED CONTROL PANEL

SECTION V

DEMONSTRATION SITE

SITE DESCRIPTION

The demonstration site was located in the 400 block of South Pearl Street in Albany, New York. Raw or combined sewage was drawn from a 91 inch combined sewer, which serves the Island Creek District in Albany. A site location map showing the demonstration site and drainage area is given in Figure 9. This drainage area is about 550 acres in size with a population of approximately 10,000. Perhaps 10-15 percent of the area is comprised of small commercial businesses with the remainder being mainly residential in nature. No light or heavy industry is located in the drainage area.

The average annual precipitation in Albany varies between 35 and 37 inches with the heaviest rainfall usually occurring in June, July, and August.

WASTEWATER FLOW AND CHARACTERISTICS

Average dry weather flow (DWF) in the 91 inch trunk sewer at the demonstration site was measured as 720 gpm. Average minimum daily flow which occurred at approximately 0500 was 610 gpm and the average maximum daily flow of 820 gpm occurred between 1000-1200. Figure 10 contains typical diurnal flow data for the Albany site.

The physical and chemical characteristics of the raw wastewater at the site were observed to be highly variable. Initially, grab samples were obtained at two-hour intervals for several twenty-four hour periods and analyzed for various constituents. During the 1972 operation, samplers were installed to collect hourly composite samples. These data are presented in Table 1 and Figures 11-13. Daily averages for the maximum, minimum, and average day during the pilot operations are presented in Table 2.

An unusually high COD peak was observed to occur frequently at about 1400 as indicated in Figure 11. Such a high COD peak was unexpected for a purely residential area. Moreover, the time of occurrence is also somewhat unusual. The source of this frequent high COD slug was not identified.

Preceding page blank

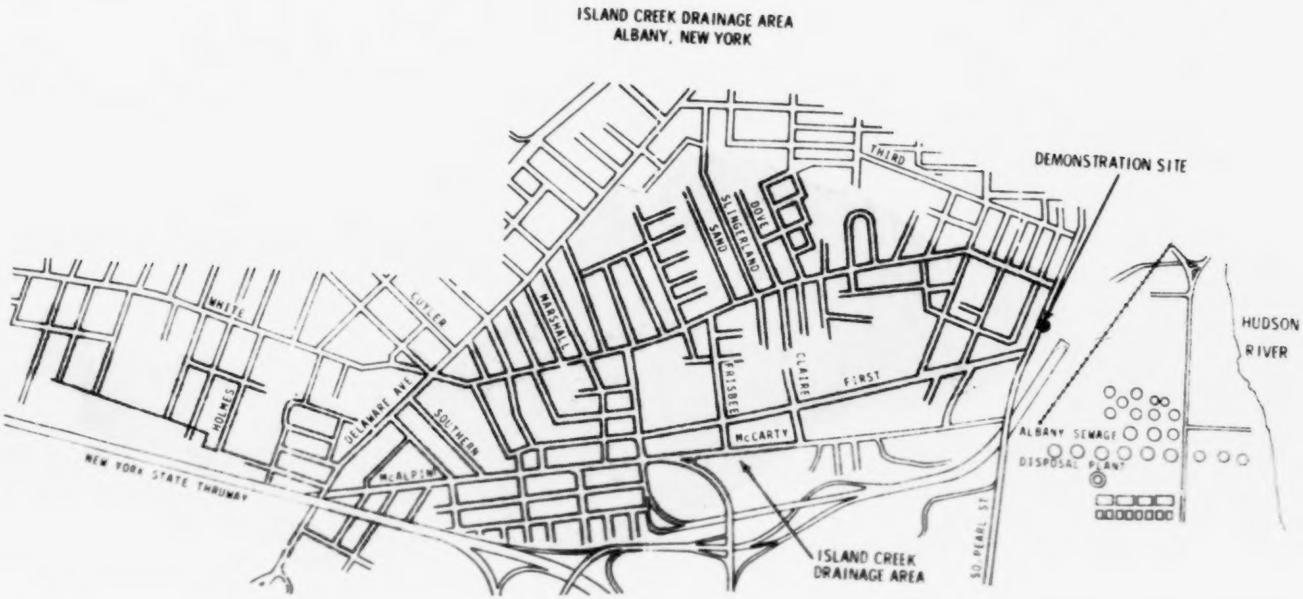

ISLAND CREEK DRAINAGE AREA
ALBANY, NEW YORK
DEMONSTRATION SITE
HUDSON RIVER
THIRD
DOVE
SLINGERLAND
SAND
MARSHALL
CUYLER
WHITE
FRISBEE
CLAIRE
FIRST
McCARTY
SOUTHERN
DELAWARE AVE
McALPIN
HOLMES
NEW YORK STATE THRUWAY
ISLAND CREEK DRAINAGE AREA
SO. PEARL ST
ALBANY SEWAGE DISPOSAL PLANT

FIGURE 9. ISLAND CREEK DRAINAGE AREA AND DEMONSTRATION SITE LOCATION

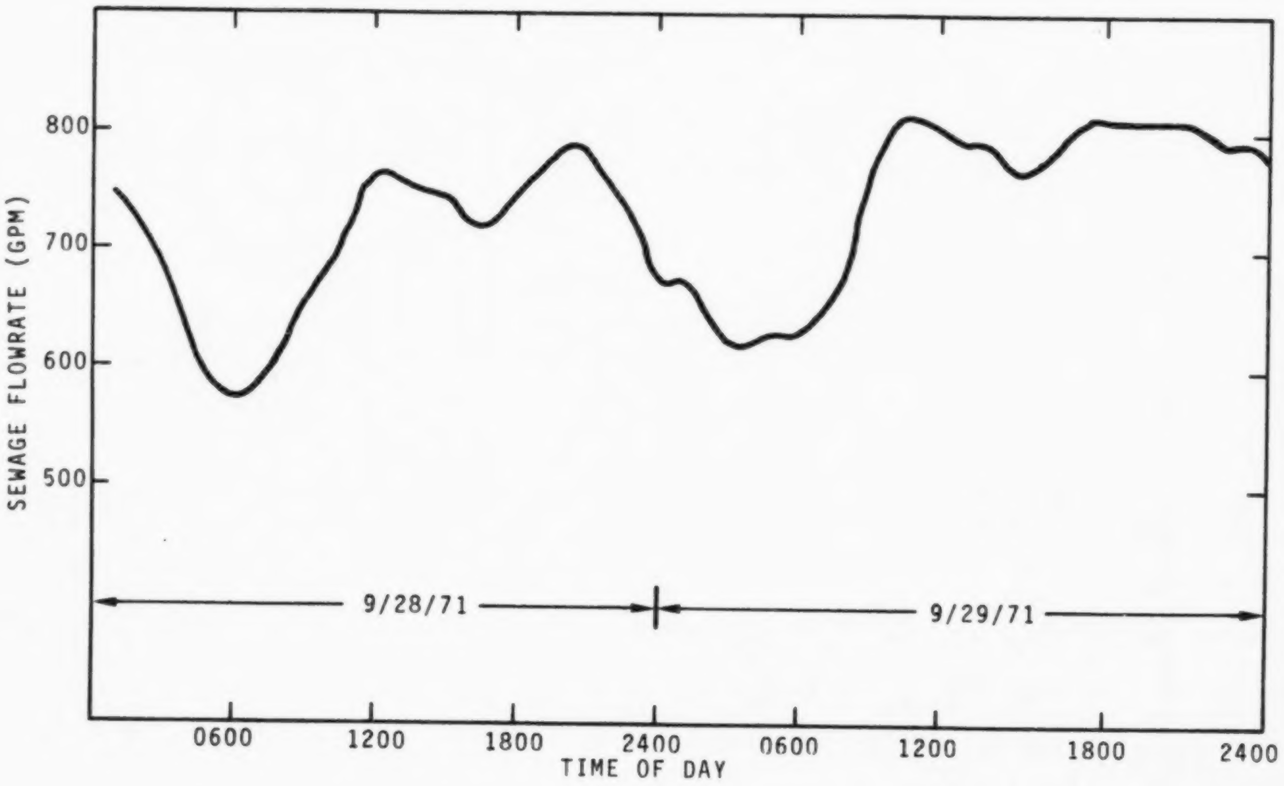


FIGURE 10. TYPICAL DIURNAL DRY WEATHER FLOW VARIATION AT ALBANY SITE

TABLE 1

DIURNAL WASTEWATER CHARACTERISTICS AT ALBANY SITE DURING DRY WEATHER

Time of Day	Suspended Solids (mg/l)	COD (mg/l)	BOD (mg/l)	Total P (mg/l)	Turbidity (JTU)
0800	370-63 188-13	778-138 288-18	108-54 83-11	42.6-10.0 27.1-13	150-34 80-13
1000	273-104 179-15	616-175 381-19	390-80 162-14	60.0-20.0 35.8-16	220-61 100-13
1200	287-27 149-13	472-206 362-18	230-62 123-10	49.8-18.0 29.4-13	148-43 86-14
1400	500-47 159-16	5200-165 713-20	678-58 162-11	64.5-12.6 28.7-16	200-31 82-14
1600	304-34 135-17	575-95 324-22	300-38 134-15	137-10.0 27.3-17	150-31 85-16
1800	420-76 172-17	572-208 325-20	200-74 129-16	31.0-16 22.3-16	274-25 105-17
2000	247-54 130-16	390-106 251-20	151-57 100-14	36.6-6.6 20.0-17	144-33 77-13
2200	322-10 123-14	460-82 218-19	160-48 93-12	26.4-4.0 15.0-14	123-27 51-11
2400	198-33 89-18	215-13 132-22	120-24 75-12	17.3-2.7 11.6-17	64-13 32-13
0200	246-14 65-17	292-32 90-24	77-12 38-13	15.6-2.7 7.4-13	78-9 21-12
0400	62-12 29-14	305-25 67-22	111-12 27-13	18.0-3.3 8.5-12	42-1 17-12
0600	206-11 68-14	979-25 162-21	110-16 41-12	29.9-3.9 12.6-14	150-3 44-12

NOTE: Numbers for each time period represent: {high value - low value
average - no. of samples}

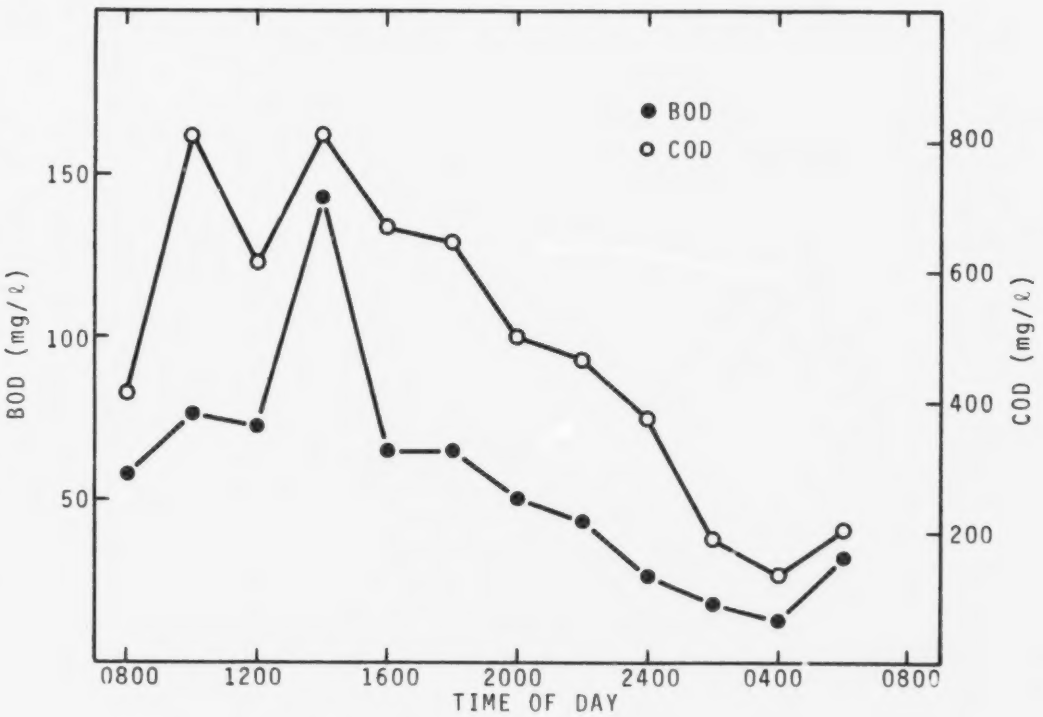


FIGURE 11. AVERAGE DIURNAL BOD AND COD FLUCTUATION AT ALBANY SITE

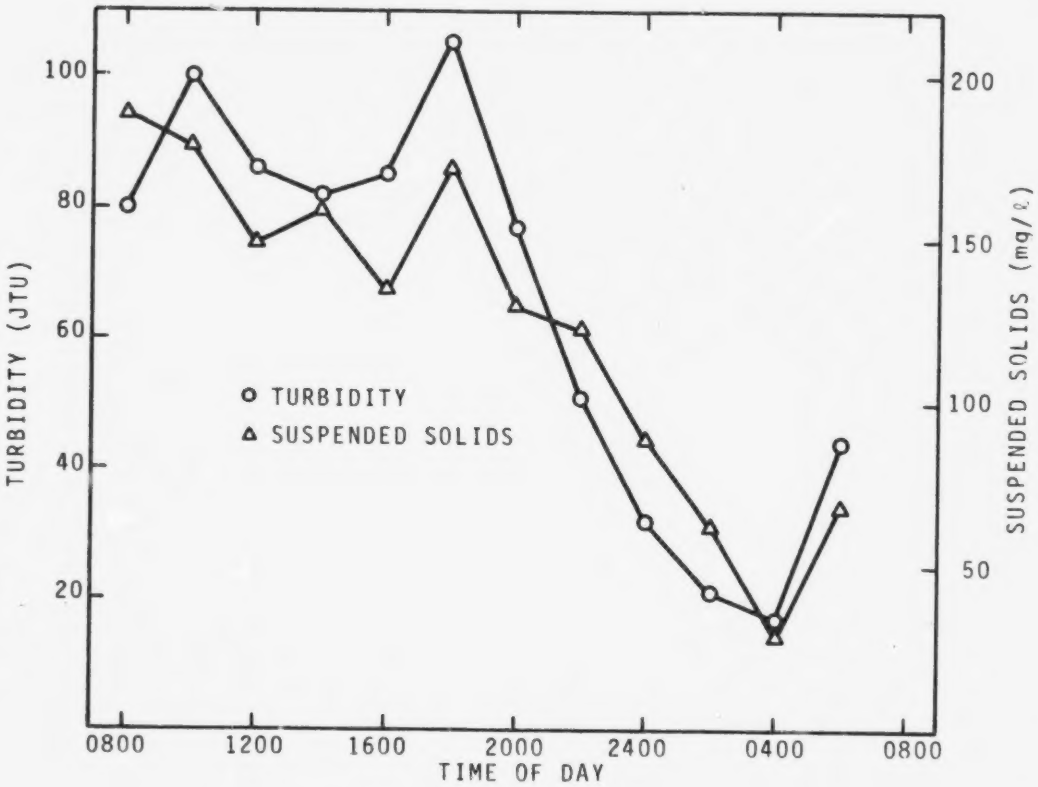


FIGURE 12. AVERAGE DIURNAL SUSPENDED SOLIDS AND TURBIDITY FLUCTUATION AT ALBANY SITE

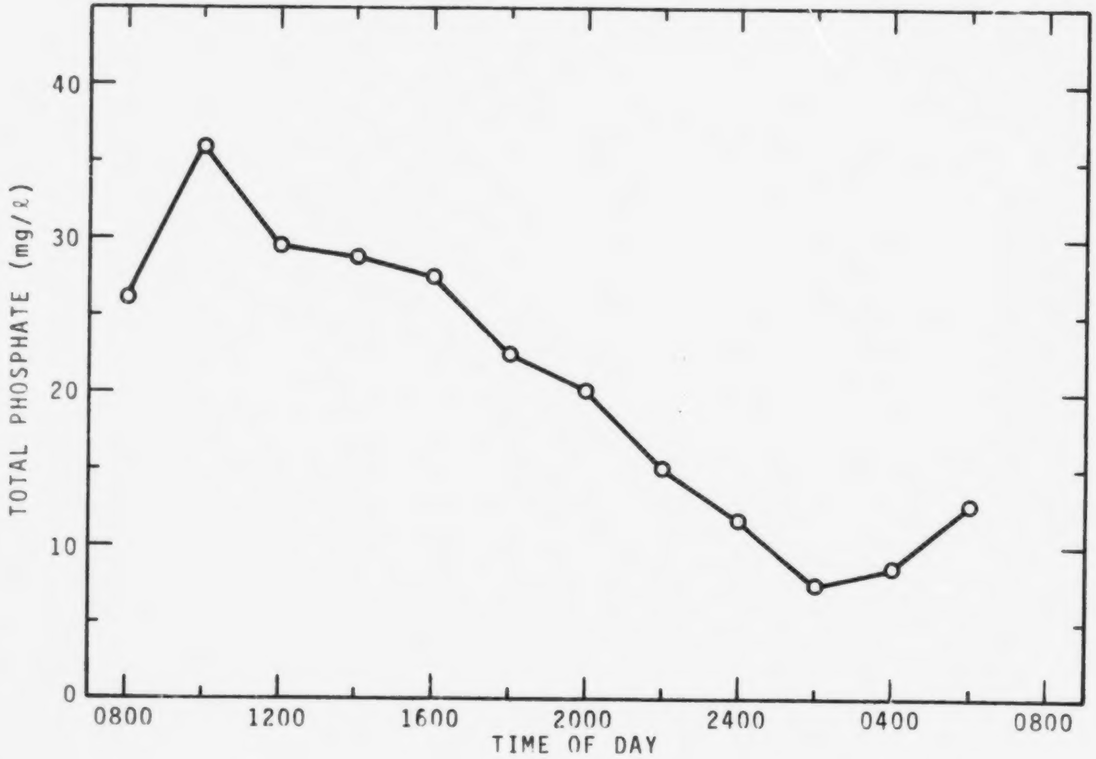


FIGURE 13. AVERAGE DIURNAL PHOSPHATE FLUCTUATIONS AT ALBANY SITE

TABLE 2

AVERAGE WASTEWATER CHARACTERISTICS AT ALBANY SITE[1]
DURING 1971 PILOT OPERATIONS

	COD	BOD	Turbidity[2]	Total Solids	Total Volatile Solids	Suspended Solids	Volatile Suspended Solids	Settleable[3] Solids	NH_3-N	Organic Nitrogen	NO_2-N	NO_3-N	Total PO_4
Maximum	483	159	315	533	268	668	150	4.0	55	25	0.2	1.0	57
Minimum	60	47	24	320	144	43	11	1.0	12	7.6	0.002	<0.1	12.6
Average	276	104	54	419	193	130	69	2.8	22	11.3	0.06	0.3	24.9
No. Days	42	37	43	18	16	45	16	11	12	12	12	9	13

---

[1] All units mg/l except as noted

[2] Units are JTU

[3] Units are ml/l after 1/2 hr. settling

SECTION VI

TREATMENT SYSTEM PERFORMANCE

GENERAL

All analytical procedures were carried out in accordance with Standard Methods(10) unless otherwise noted. During the course of the field work, most of the analytical work was subcontracted to Environment One Corporation of Schenectady, New York. The New York State Department of Environmental Conservation provided significant analytical support to this program, especially in characterizing the waste stream at the demonstration site.

Jar tests were carried out routinely in support of the pilot plant activities. The general procedure involved addition of the desired quantity of carbon slurry to one liter of sewage and then adjustment of the pH to 4 with sulfuric acid prior to addition of 200 mg/l of alum. Samples were then subjected to a ten minute rapid mix whereupon the pH was adjusted to 7 with $Ca(OH)_2$. Rapid mixing was continued for an additional five minutes before addition of 2 mg/l of polyelectrolyte. Following an additional half minute of rapid mixing, the sample was flocculated at 10 rpm for five minutes and was then allowed to settle for twenty minutes. Supernatant samples were decanted for analytical determinations. In most instances, these samples were analyzed for BOD and COD directly. Those cases in which samples were filtered through 0.45μ membrane filters are identified in the text as "soluble" BOD and COD determinations.

PLANT OPERATION

During the course of the pilot plant studies, both virgin carbon and regenerated carbon were used in the treatment system. When virgin carbon (first cycle) was employed for any run in the pilot plant, alum was added to the carbon slurry (6 percent carbon by weight) in a chemical feed tank and the mixture was acidified to pH 2 with sulfuric acid prior to use. This simulated the conditions of a regenerated carbon slurry which had been acidified to reclaim alum. Injection of this acidified carbon-alum slurry into the raw wastewater resulted in a pH of 3.5-4.

Careful control of the pH within the system was critical to proper process performance. The laboratory studies showed that, in order to consistently achieve good flocculation, it was essential to provide several minutes of carbon contact with the wastewater prior to formation of the hydrous aluminum oxide. In the pilot plant, this was achieved by maintaining the pH below 4 for the first five minutes of contact and then adjusting the pH to 6.5-7 with a lime slurry. It was observed, in the course of the pilot studies, that if the pH was allowed to rise above pH 4 within the first few minutes, fine carbon particles were carried over from the tube settler causing rapid filter plugging. Moreover, under these conditions, the turbidity of the filter effluent increased considerably. A three percent lime slurry was used to adjust the pH in the system. Lime feed was controlled automatically on the basis of pH.

Throughout the pilot operations, the alum [$Al_2(SO_4)_3 \cdot 18H_2O$] dose was held constant at approximately 200 mg/l. It was determined that the flocculation-sedimentation process deteriorated considerably if the alum dose was reduced much below the 200 mg/l level. On the other hand, the carbon dose could be varied from 0-1100 mg/l while maintaining the alum dose at 200 mg/l with no serious effect on the flocculation-sedimentation efficiency.

Two types of powdered activated carbon were used in the study: Aqua Nuchar (product of WESTVACO) and Darco XPC (product of ICI America, Inc.). Analyses showed Aqua Nuchar A to be approximately 90 percent fixed carbon while the Darco product contained only 70-80 percent fixed carbon. Both carbons performed comparably in the pilot studies at equal fixed carbon doses. The relatively low fixed carbon content of the Darco XPC is not surprising since this is an unwashed grade of lignite carbon. After several adsorption/regeneration cycles, the differences between this and a washed grade of carbon may not be significant. However, it was decided to use the higher grade Aqua Nuchar A for the bulk of the pilot operations.

Three different high molecular weight anionic polyelectrolytes were used in the pilot study: Atlasep 2A2 (product of ICI America, Inc.), Decolyte 930 (product of Diamond Shamrock Chemical Company), and Purifloc A-23 (product of Dow Chemical Company). All of these polymers were observed to produce large, rapidly settling floc particles. Each of these polyelectrolytes performed satisfactorily at a dose of 2 mg/l.

Initially, high solids carryover from the tube settler was observed when the system was operated at a flow rate greater than 50 gpm. It was determined that this problem was the result of poor flow distribution within the unit. Subsequently, a new influent distributor was installed in the tube settler and the unit performed well at the design flow of 70 gpm. This represents an overflow rate of 2880 gpd/ft^2.

Under these conditions, the turbidity of the effluent from the tube settler was consistently <2 JTU. Filter runs averaged ten hours at a filter loading rate of 4.4 gpm/ft^2. Backwash was initiated at a terminal head loss of approximately 10 psi.

Sludge withdrawal was accomplished by pumping the sludge from the base of the two hopper bottoms of the pilot tube settler. Since there was no mechanical collection system in the tube settler, it was necessary to withdraw the sludge at a rate of approximately nine percent of the plant flow. This sludge rapidly settled to 10-20 percent of its original volume in the sludge storage tank. Therefore, it is reasonable to expect that in a large clarifier with a mechanical scraper, sludge volume would be 1-2 percent of the plant flow. However, the absence of a mechanical scraper in the tube settler did cause an additional problem. Channeling tended to occur during sludge withdrawal even though the sludge pump was operated on a 90 seconds on, 30 seconds off cycle to minimize this problem. Consequently, efficient withdrawal of sludge was not accomplished and the tube settler tended to fill with sludge after about 48 hours operation. When this occurred, solids tended to overflow from the tube settler and onto the filter. The only feasible means found to correct this condition was to completely drain the tube settler prior to continuing operations. Once again, this problem should not occur in a large clarifier or tube settler with a mechanical scraper.

At no time during the operations was hydrogen sulfide detected in the plant effluent. Even after the system had been idle for several days an H_2S odor was generally not detected in the closed process trailer. However, in warm weather if the system was not in operation and sludge was allowed to remain in the tube settler for 2-3 days time, H_2S was observed to form. In actual plant operation, the sludge age should be nowhere near two days and thus hydrogen sulfide should not be a problem.

The carbon sludge was readily dewaterable in a Bird six-inch solid bowl centrifuge. Dewatered sludge ranged from 20-35 percent solids at 70 percent capture with no conditioning polymer.

Initial operation at a pool depth of 0.35 inch produced sludge containing 26 percent solids. This sludge was very viscous and extremely difficult to pump to the regeneration facility. Increasing the pool depth to 0.5 inch produced a much more pumpable, 22 percent solids sludge. It was found that rapid mixing of the dewatered sludge reduced its viscosity rendering it much more easily pumped.

Solids capture was found to be improved by treating the sludge with the same polymer used in the waste treatment process. A polymer dose of 2 lbs/ton dry solids increased solids capture to greater than 95 percent. Since no polymer screening tests were conducted, it is expected that the 2 lbs/ton dose can be reduced substantially by selection of the proper conditioning agent.

It was found that as the sludge aged, the polymer dose required for conditioning increased. Sludge more than 2-3 days old required polymer doses as high as 4 lbs/ton to achieve the same solids capture in the centrifuge.

COMBINED SEWAGE TREATMENT

The treatment system performed well during the course of nine storm events which occurred during the summer and fall of 1971 and in the spring of 1972 at the Albany site. These storm events ranged in duration from 2 to 7 hours with the total rainfall during a single event ranging from 0.05 to 1.13 inches. Thus the combined sewage flows handled by the treatment system are representative of a range of conditions typical of the Albany area.

Operational data for the pilot treatment system during these storms are given in Table 3. Turbidity, suspended solids, COD, and BOD data for the storms are presented in Figures 14-32. Plant detention times (listed in Table 3) should be taken into account when comparing effluent quality data with influent waste composition in these figures. Throughout the course of all of these storms, plant effluent turbidity rarely exceeded 1 JTU and effluent suspended solids ranged from <1-18 mg/l, while the influent suspended solids exceeded 8800 mg/l at the peak of one storm. Effluent COD, BOD, and suspended solids averaged 23, 6.0, and 4.2 mg/l, respectively. This represents average removals of 94 percent COD, 94 percent BOD, and 99 percent suspended solids. During the peak pollutant loadings of these storms the effluent quality remained essentially unaffected resulting in removals as high as 99 percent COD, 99 percent BOD, and 99.9 percent suspended solids.

Inspection of the data in Figures 20, 28, 30, and 32 reveals that the greatest portion of the COD in the combined sewage at the Albany site was insoluble. However, these data also show that the soluble fraction of the COD is of significant magnitude. This suggests that although solids removal is perhaps the most important factor in combined sewage treatment, it is not sufficient to produce a high quality effluent.

TABLE 3

OPERATIONAL DATA DURING STORM FLOWS

Date	Total Rainfall (inches)	Combined Flow Duration	Plant Flow (gpm)	Detention Time (minutes)	Carbon Dose (mg/l)
7/13/71	0.39	2030-0200	42	85	1300
7/19/71	0.55	1100-1600	70	50	625
7/29/71	0.30	1545-2000	50	70	800
9/16-17/71	0.46	2100-2215	40	88	800
		2215-0100	75	47	800
5/2/72	0.20	0330-0730	40	88	570
5/16/72	0.05	0215-0430	40	88	500
5/16/72	0.15	0530-0730	40	88	500
5/16-17/72	0.45	2000-0230	40	88	500

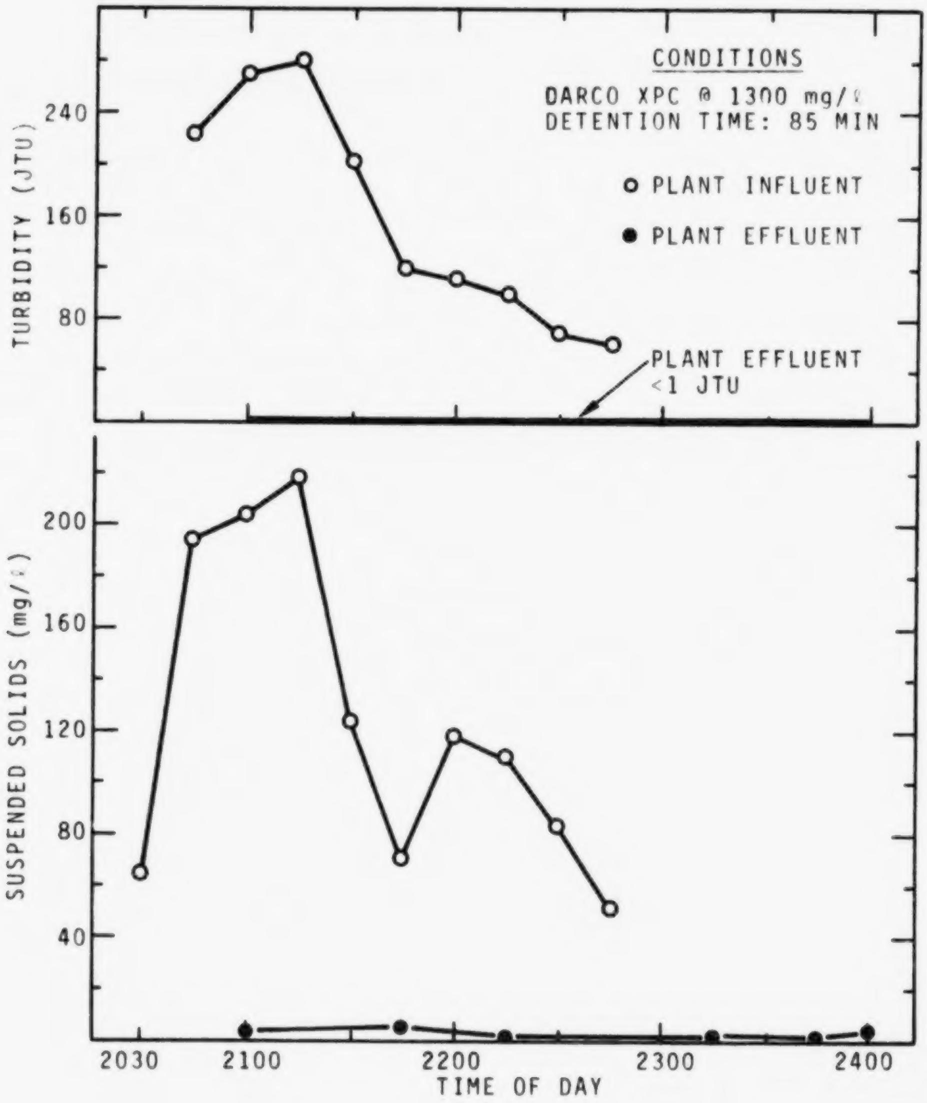


FIGURE 14. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 7/13/71

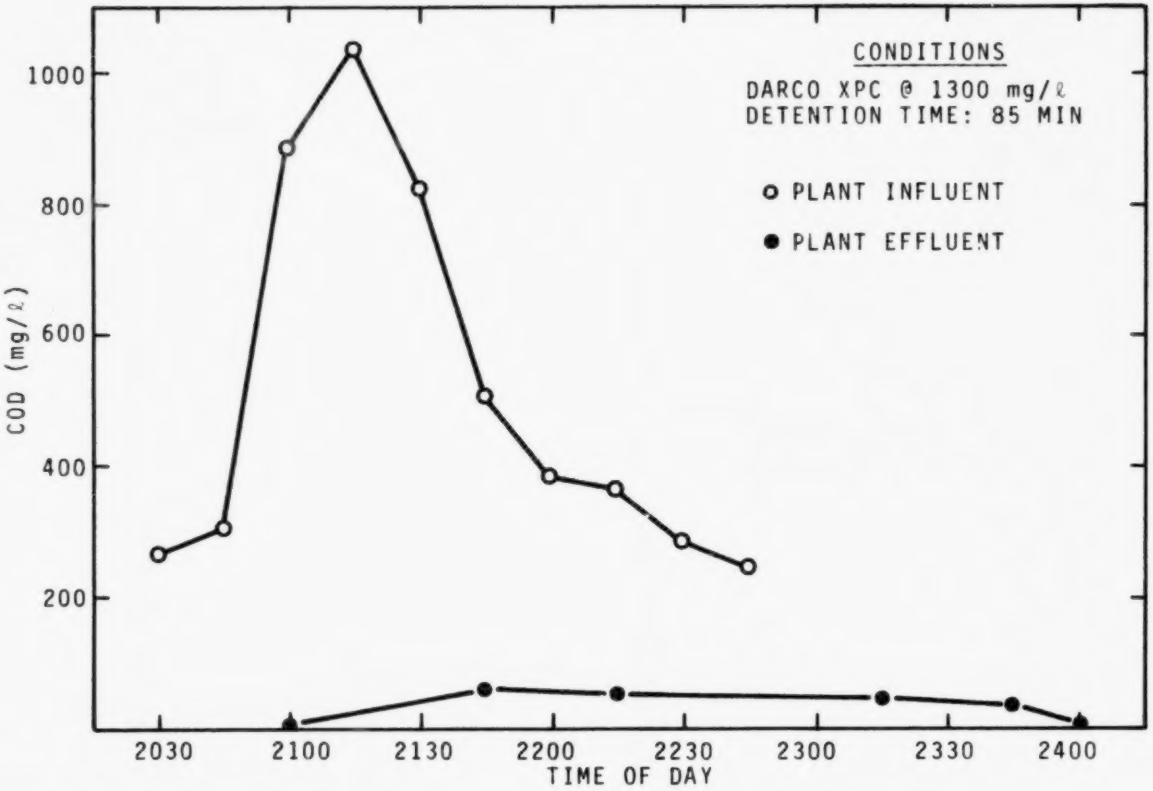


FIGURE 15. STORM EFFECT ON COD - 7/13/71

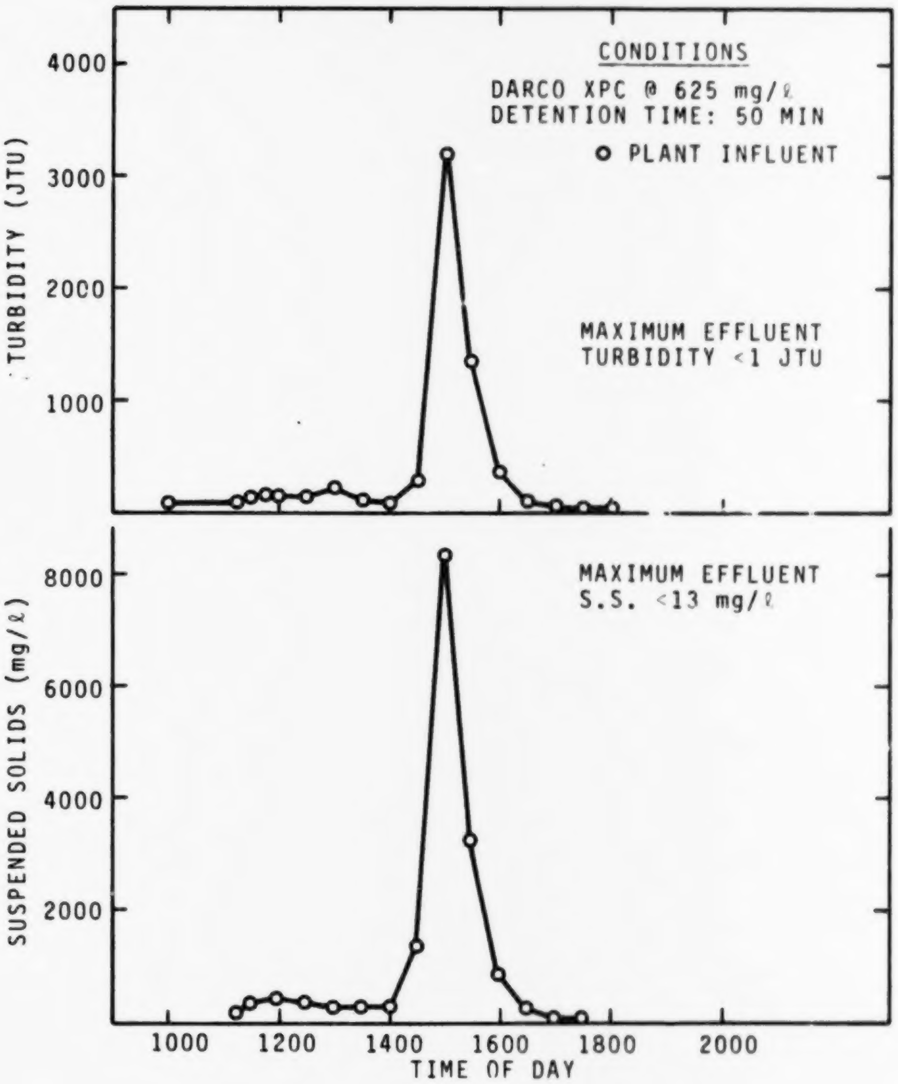


FIGURE 16. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 7/19/71

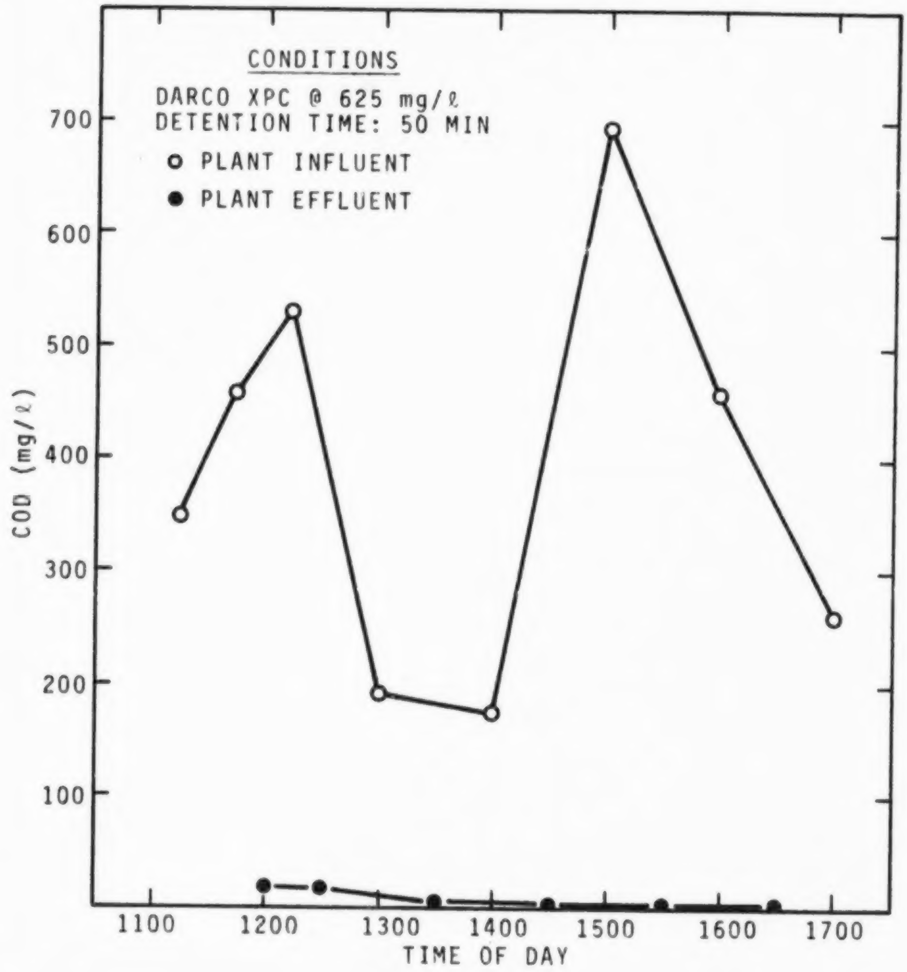


FIGURE 17. STORM EFFECT ON COD - 7/19/71

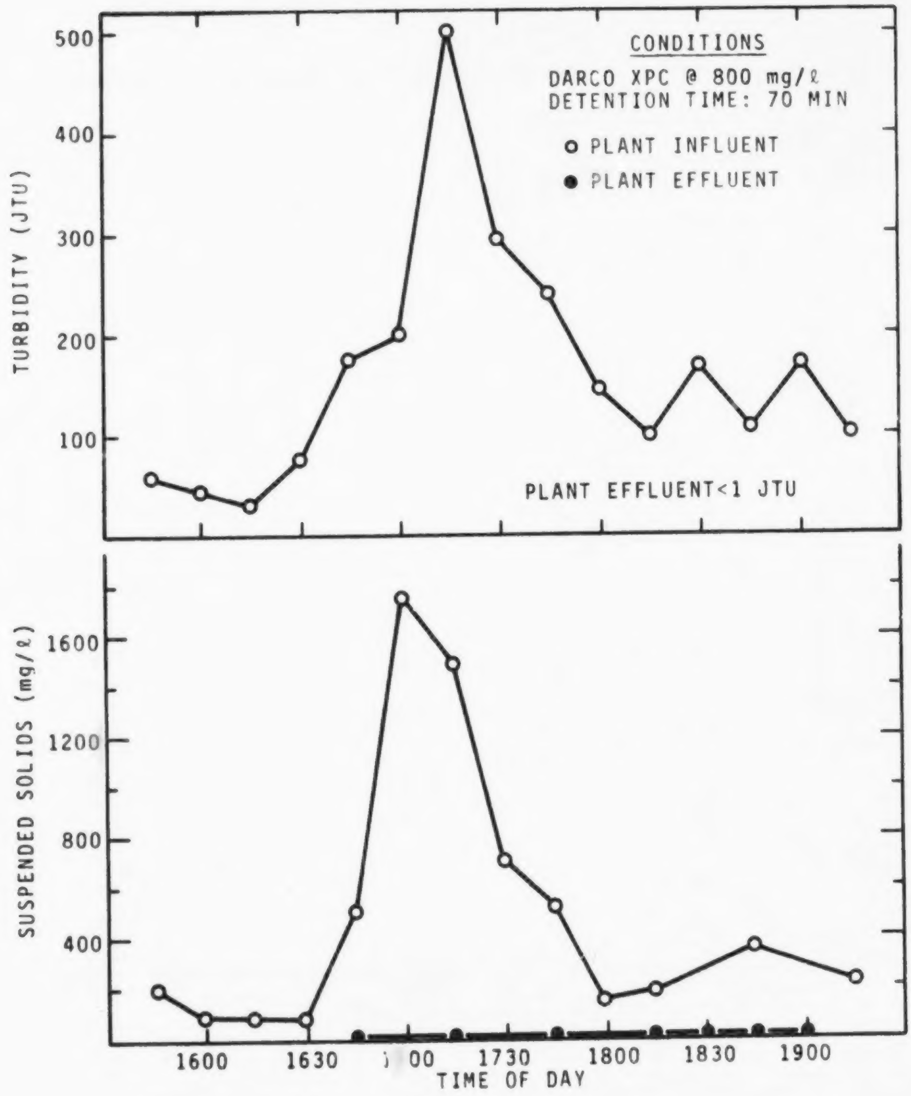


FIGURE 18. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 7/29/71

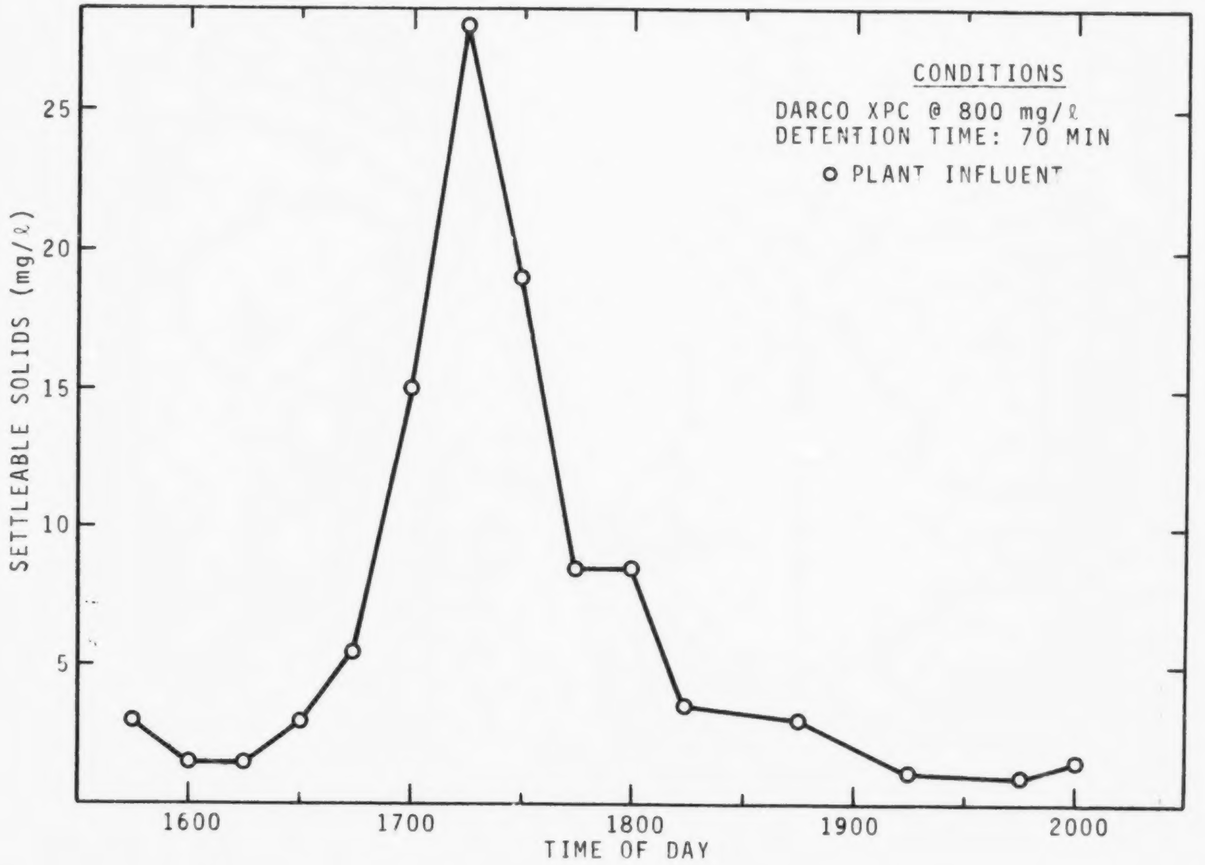


FIGURE 19. STORM EFFECT ON SETTLEABLE SOLIDS - 7/29/71

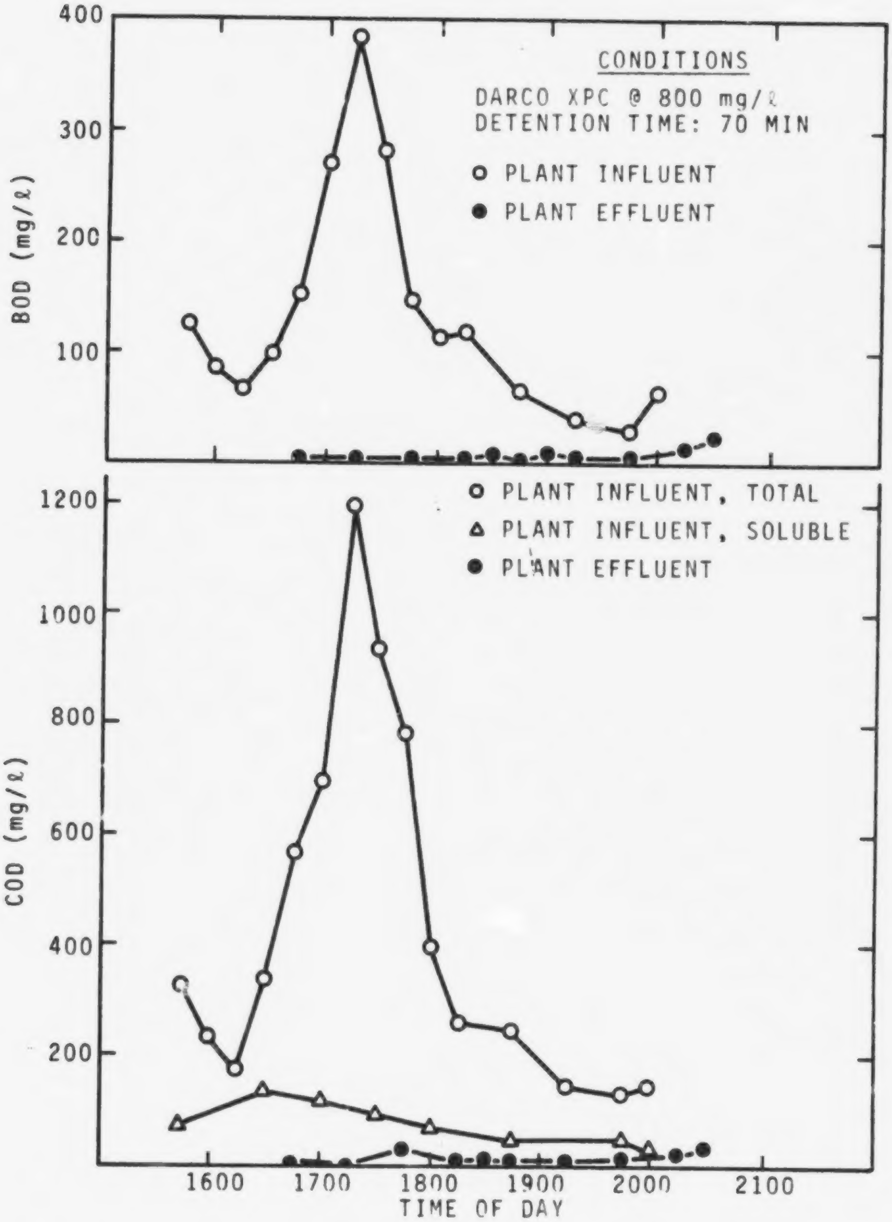


FIGURE 20. STORM EFFECT ON BOD AND COD - 7/29/71

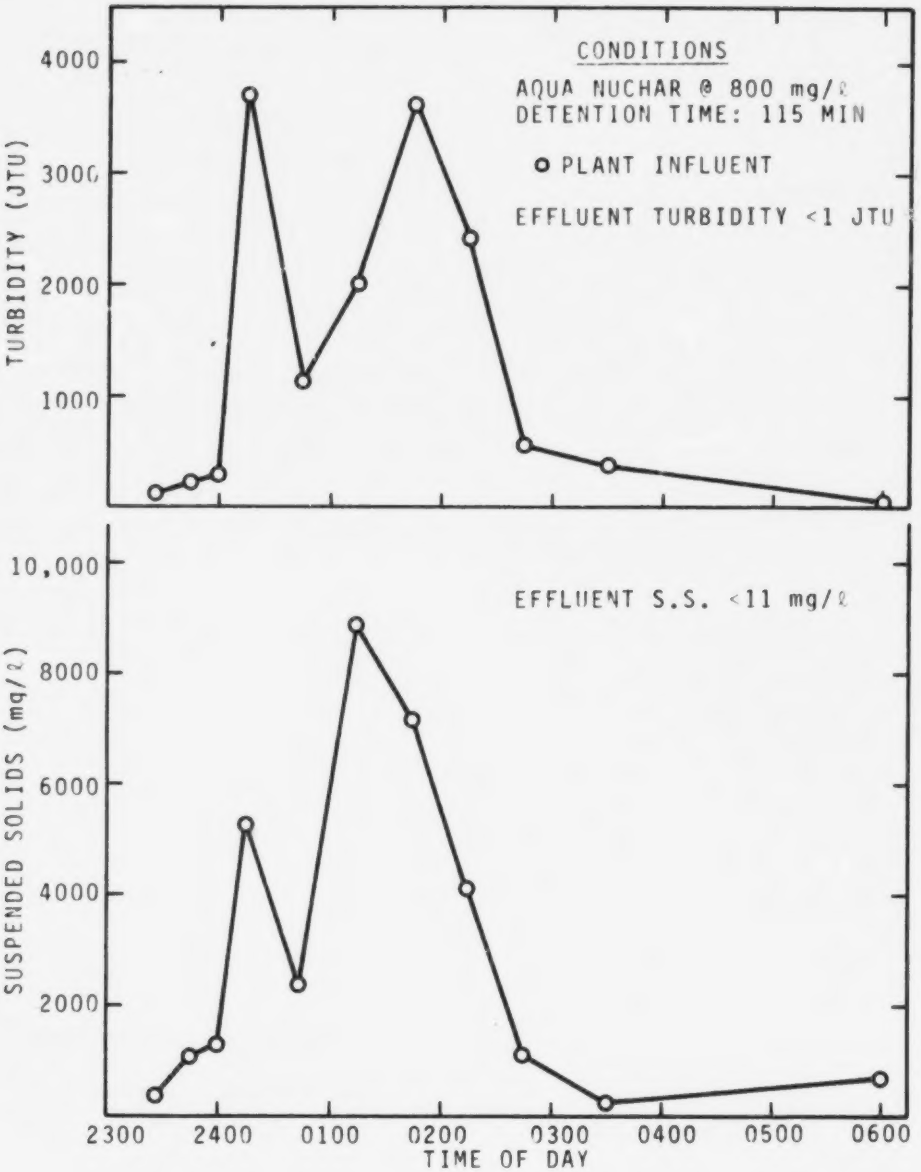


FIGURE 21. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 9/13-14/71

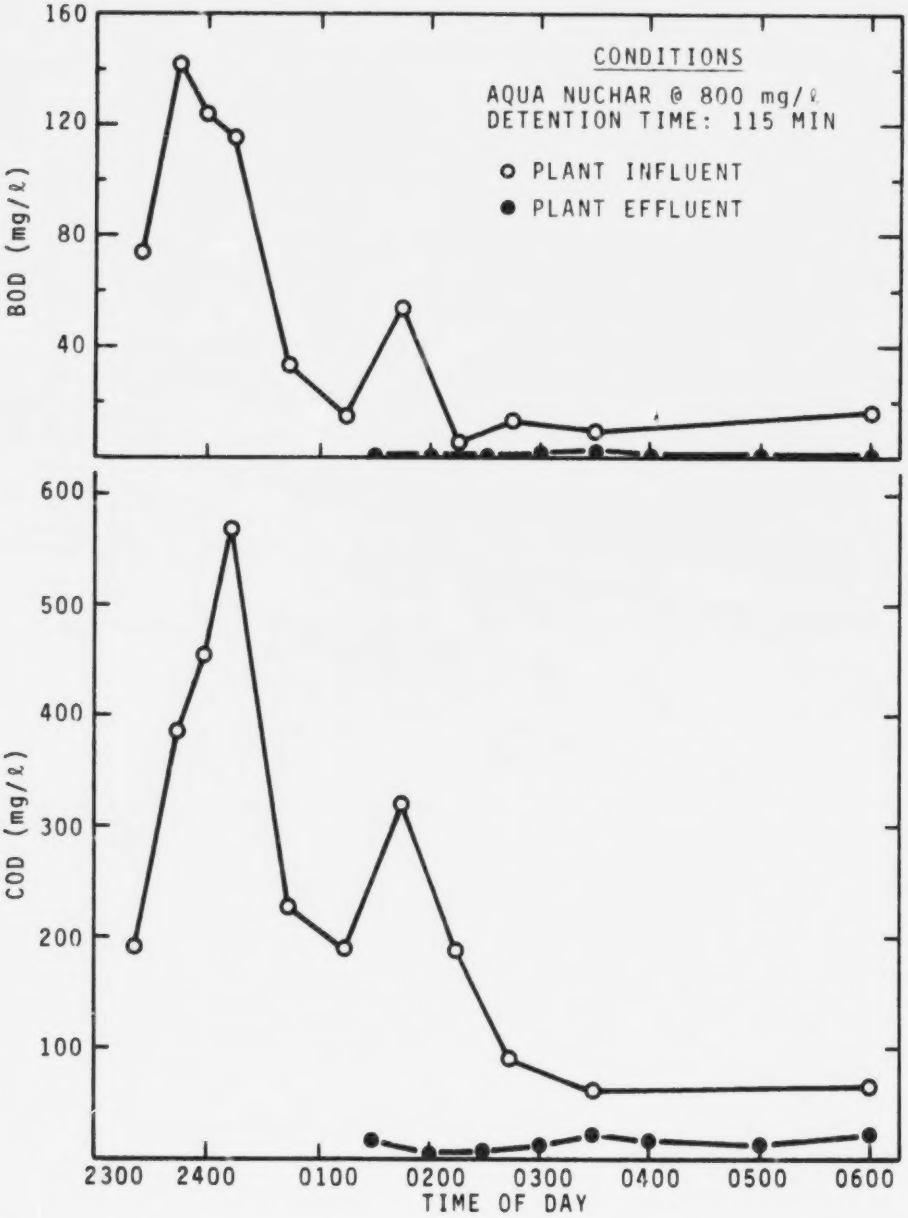


FIGURE 22. STORM EFFECT ON BOD AND COD - 9/13-14/71

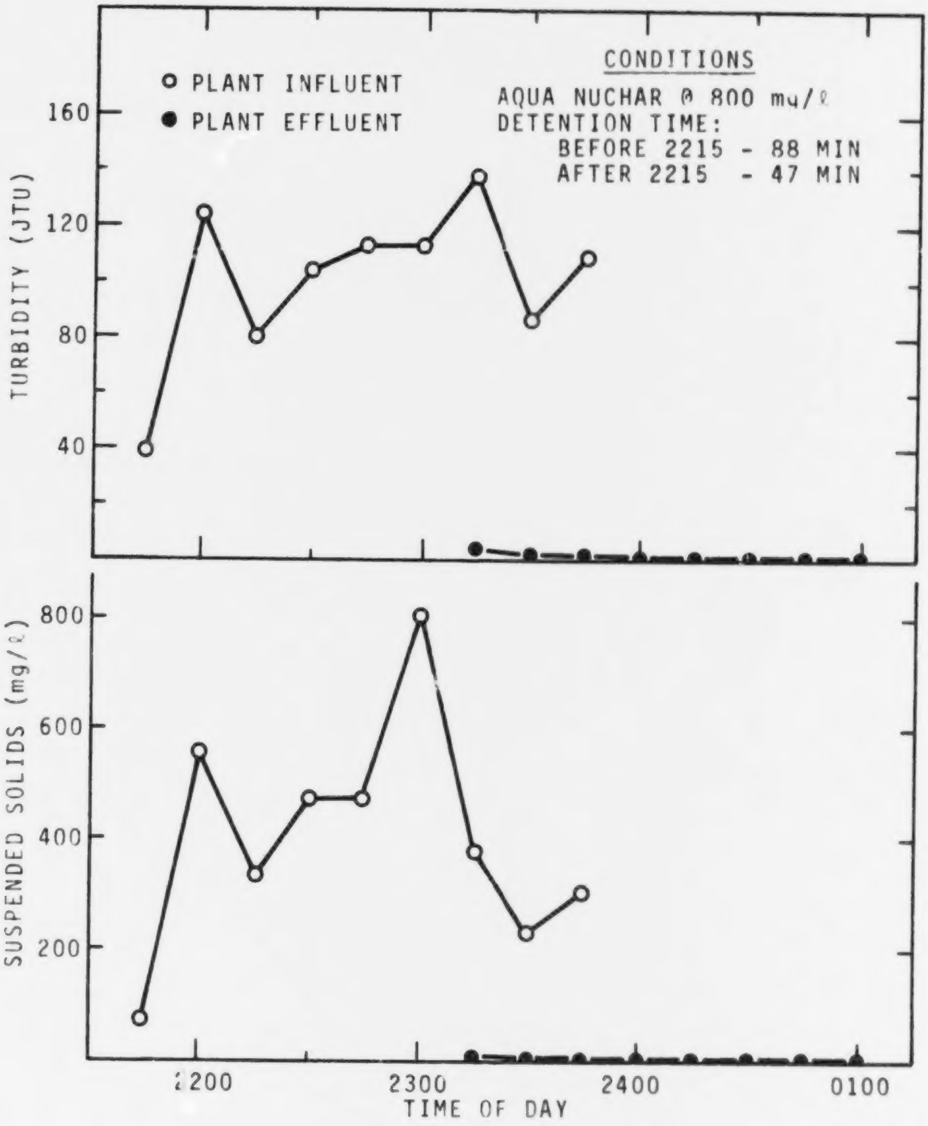


FIGURE 23. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 9/16-17/71

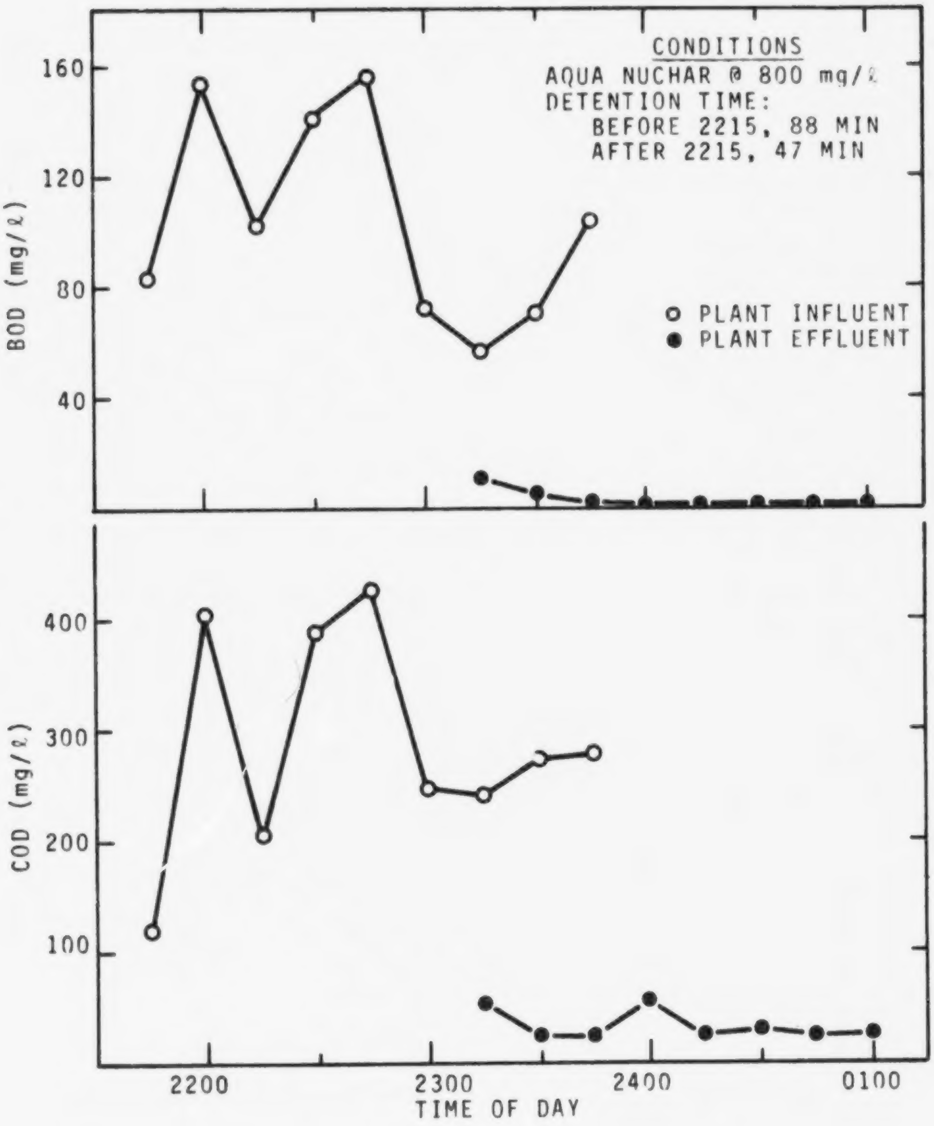


FIGURE 24. STORM EFFECT ON BOD AND COD - 9/16-17/71

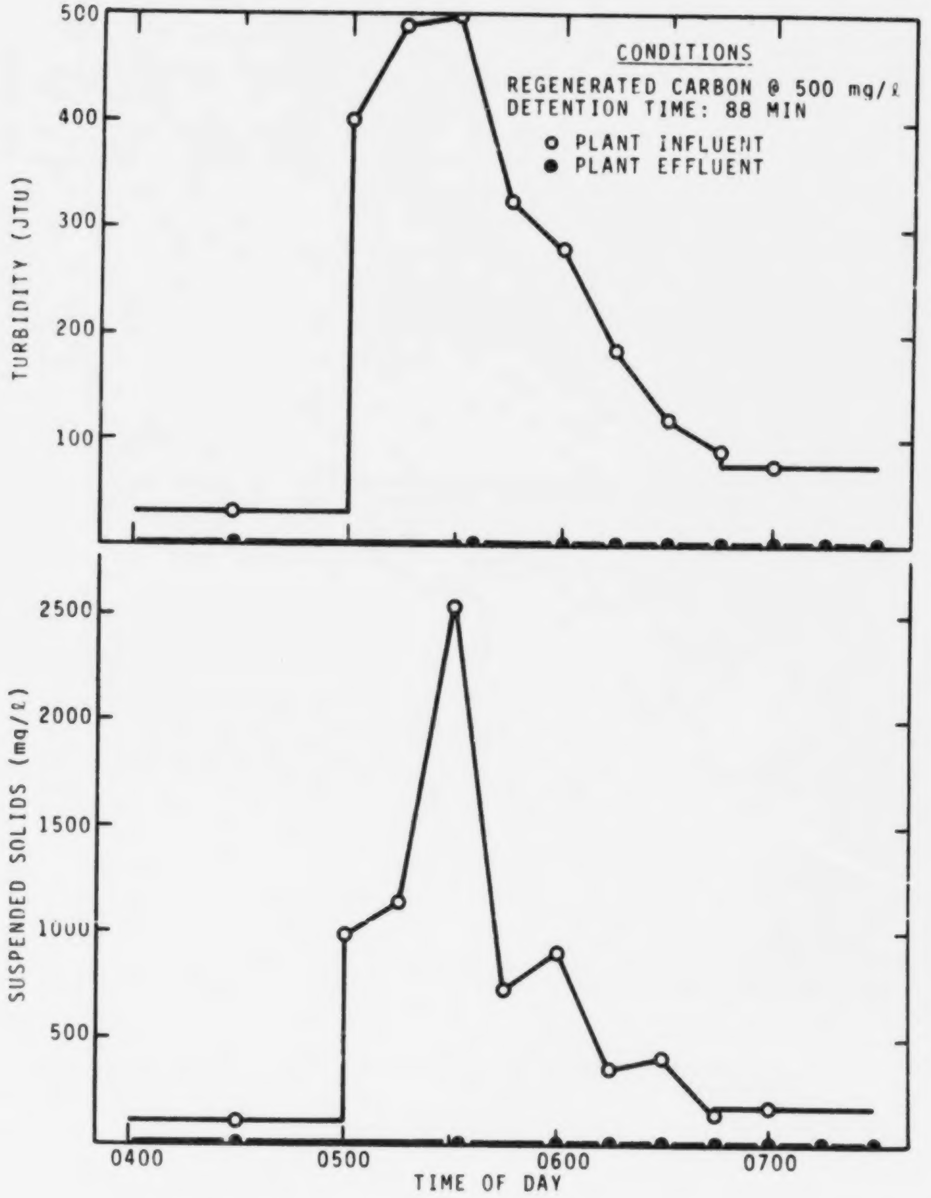


FIGURE 25. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/2/72

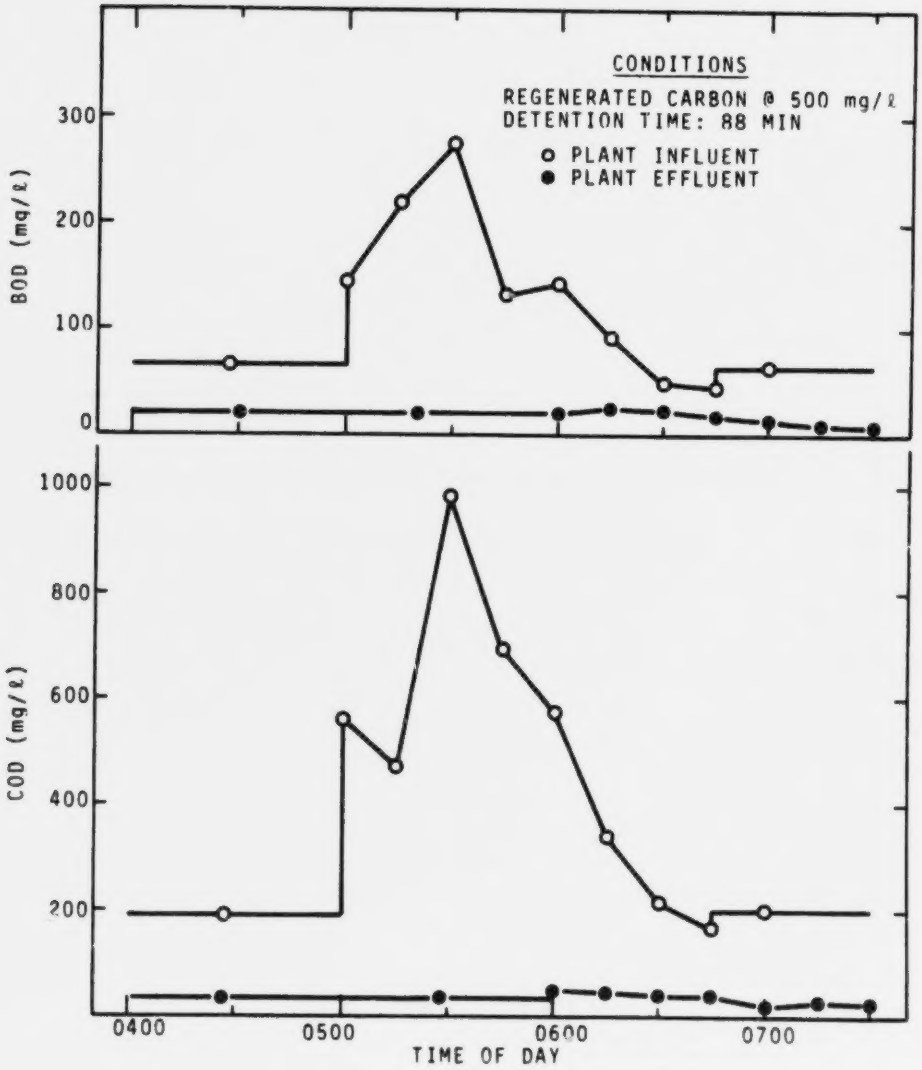


FIGURE 26. STORM EFFECT ON BOD AND COD - 5/2/72

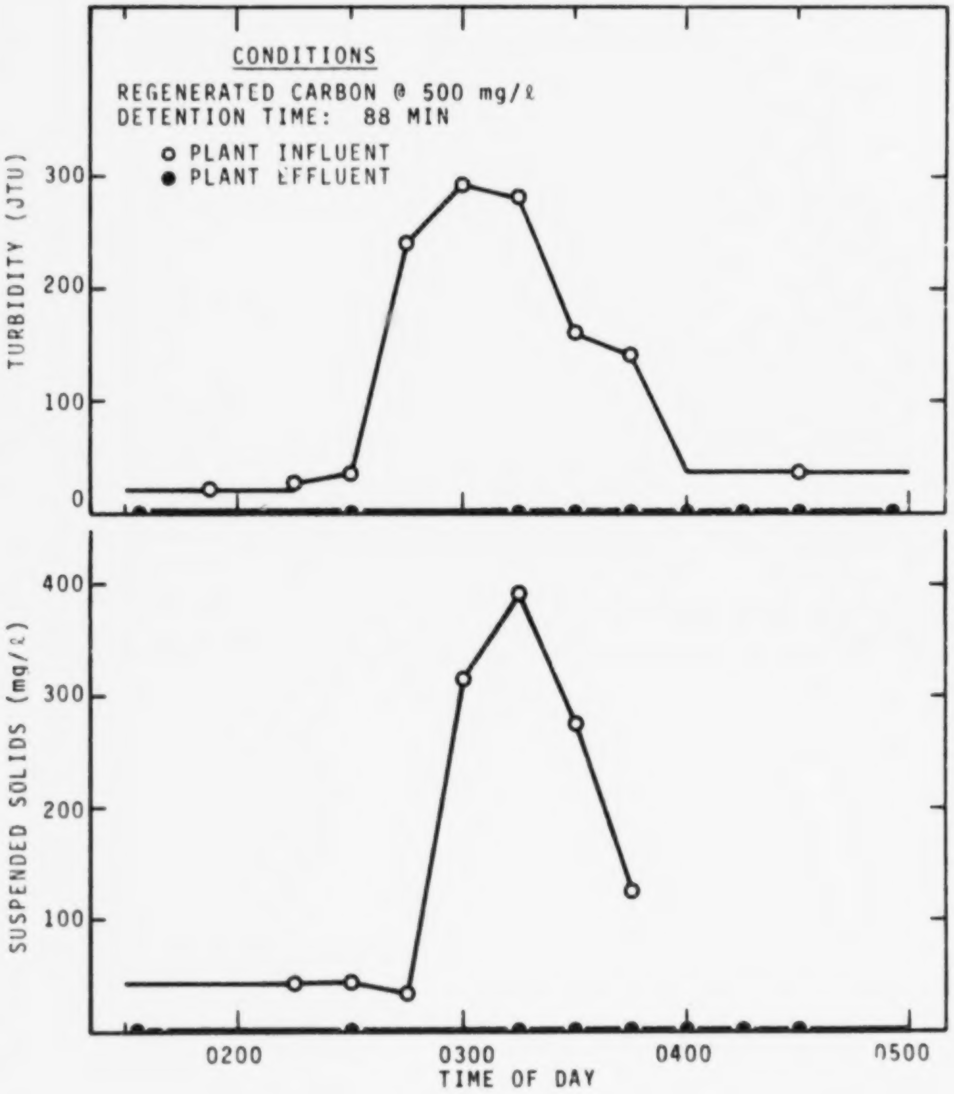


FIGURE 27. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/16/72

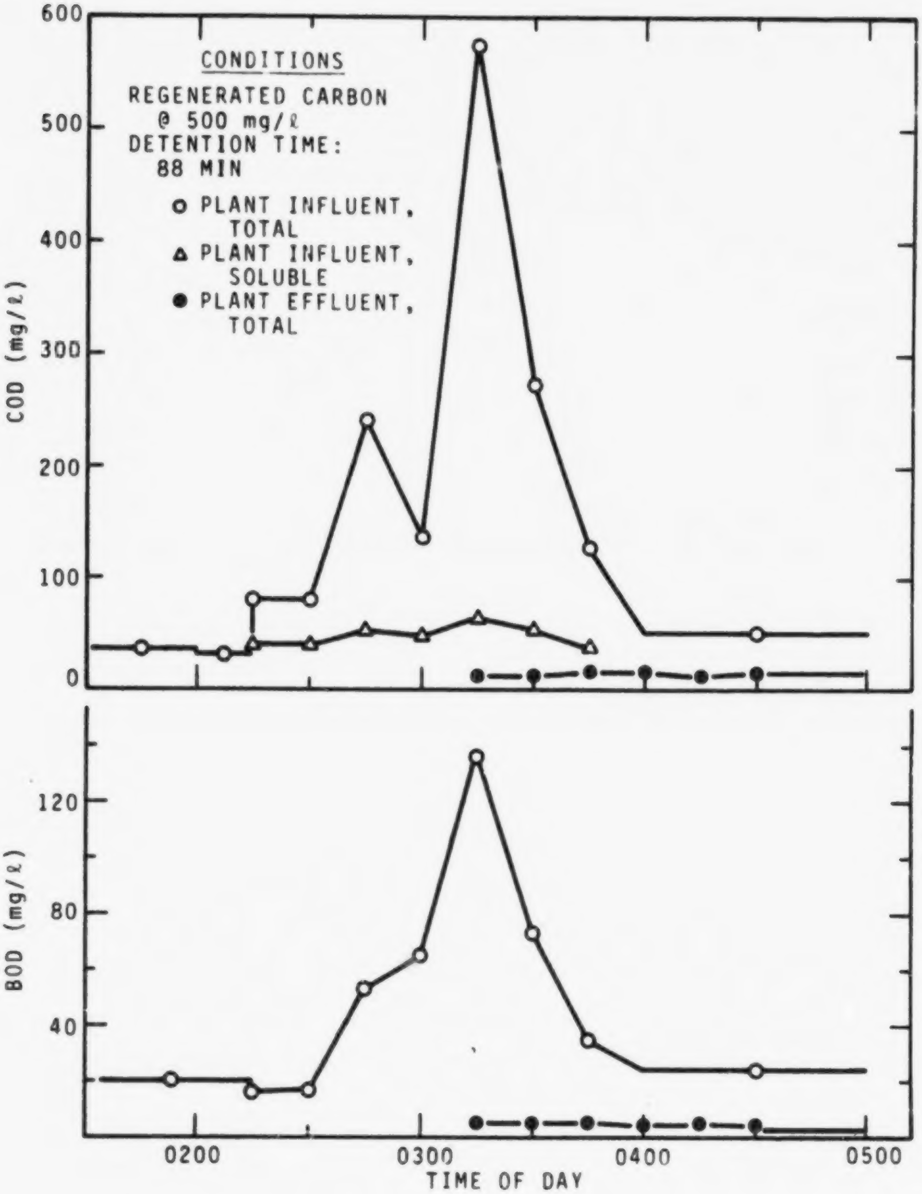


FIGURE 28. STORM EFFECT ON COD AND BOD - 5/16/72

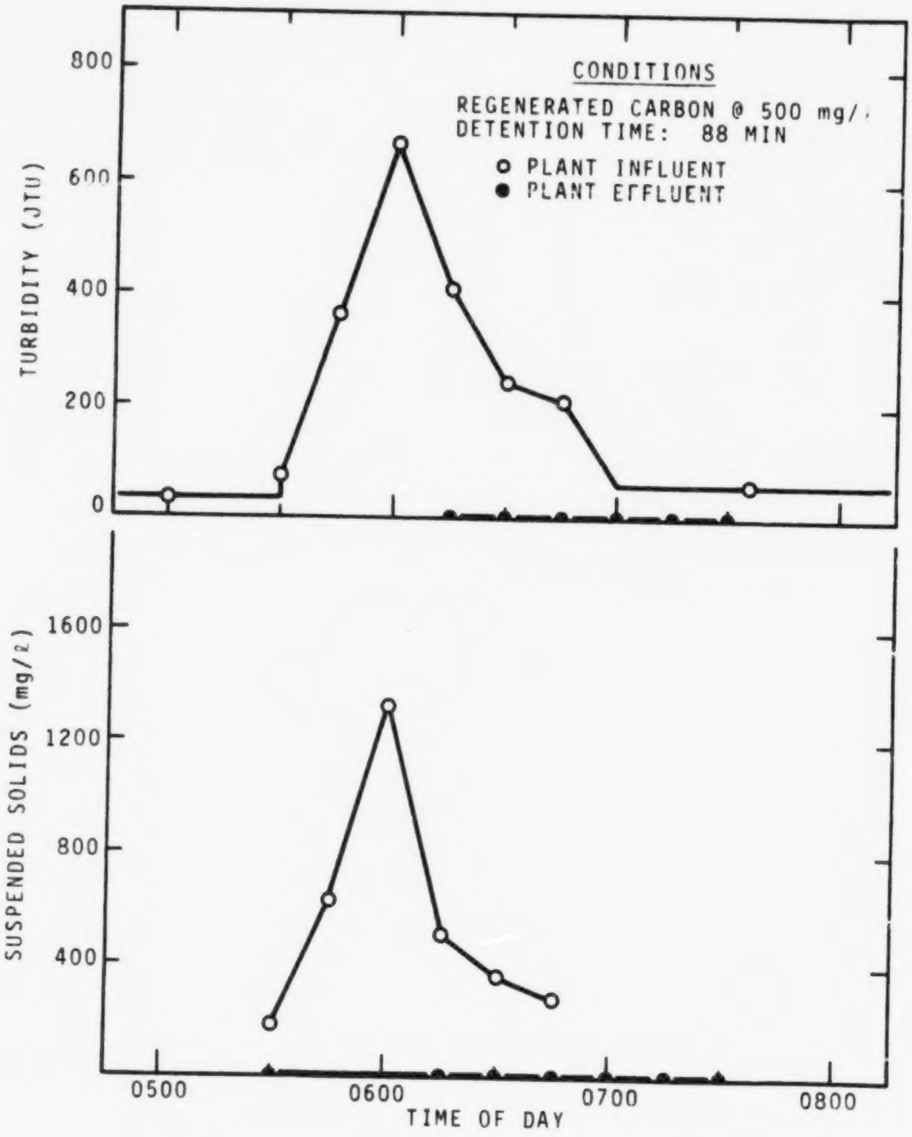


FIGURE 29. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/16/72

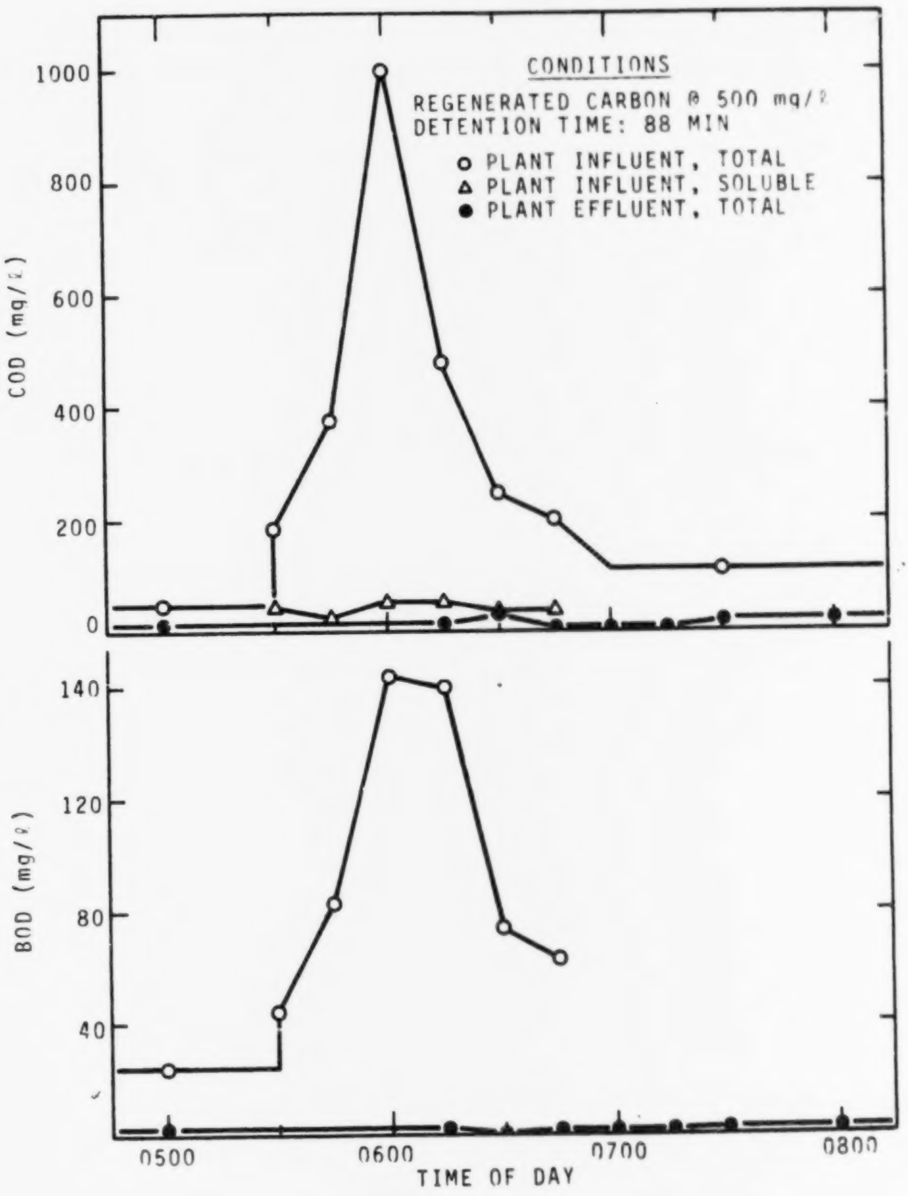


FIGURE 30. STORM EFFECT ON COD AND BOD - 5/16/72

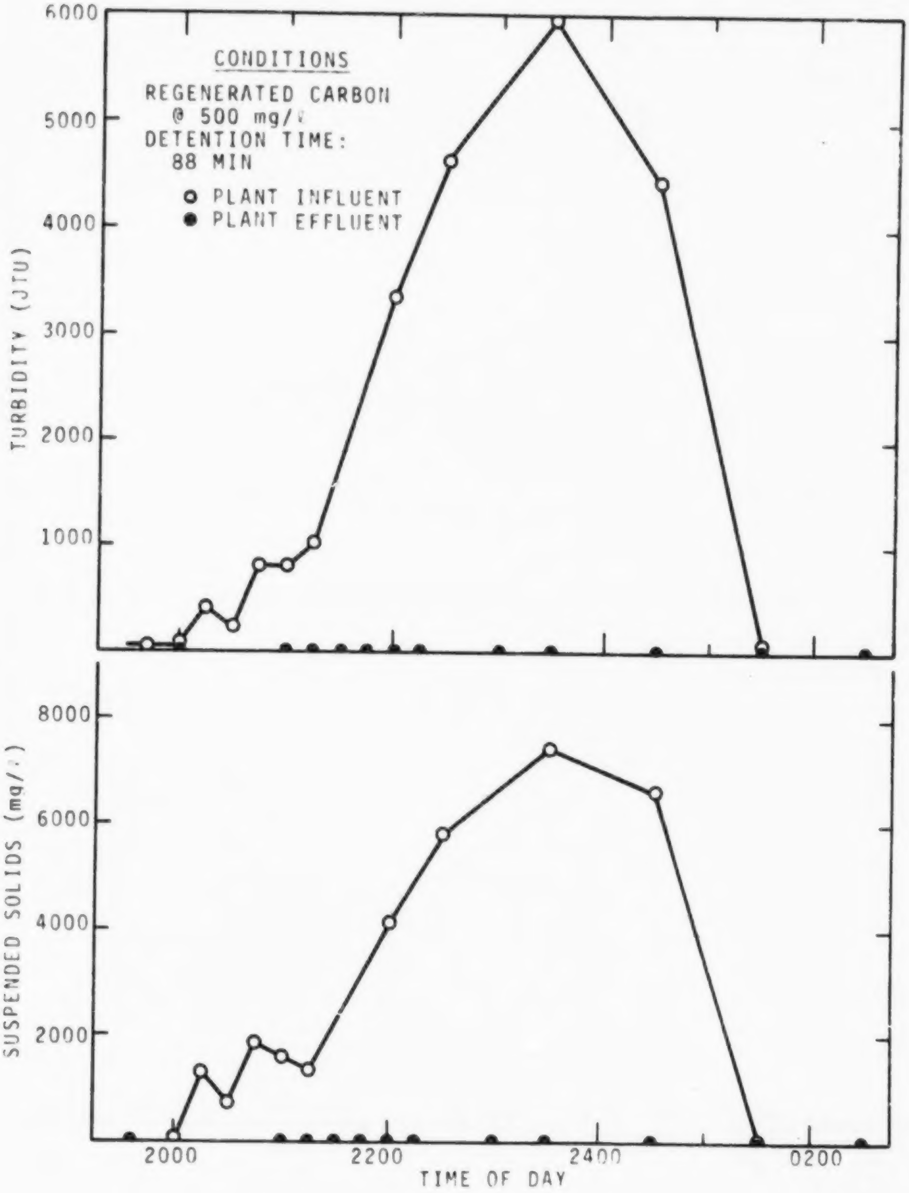


FIGURE 31. STORM EFFECT ON TURBIDITY AND SUSPENDED SOLIDS - 5/16-17/72

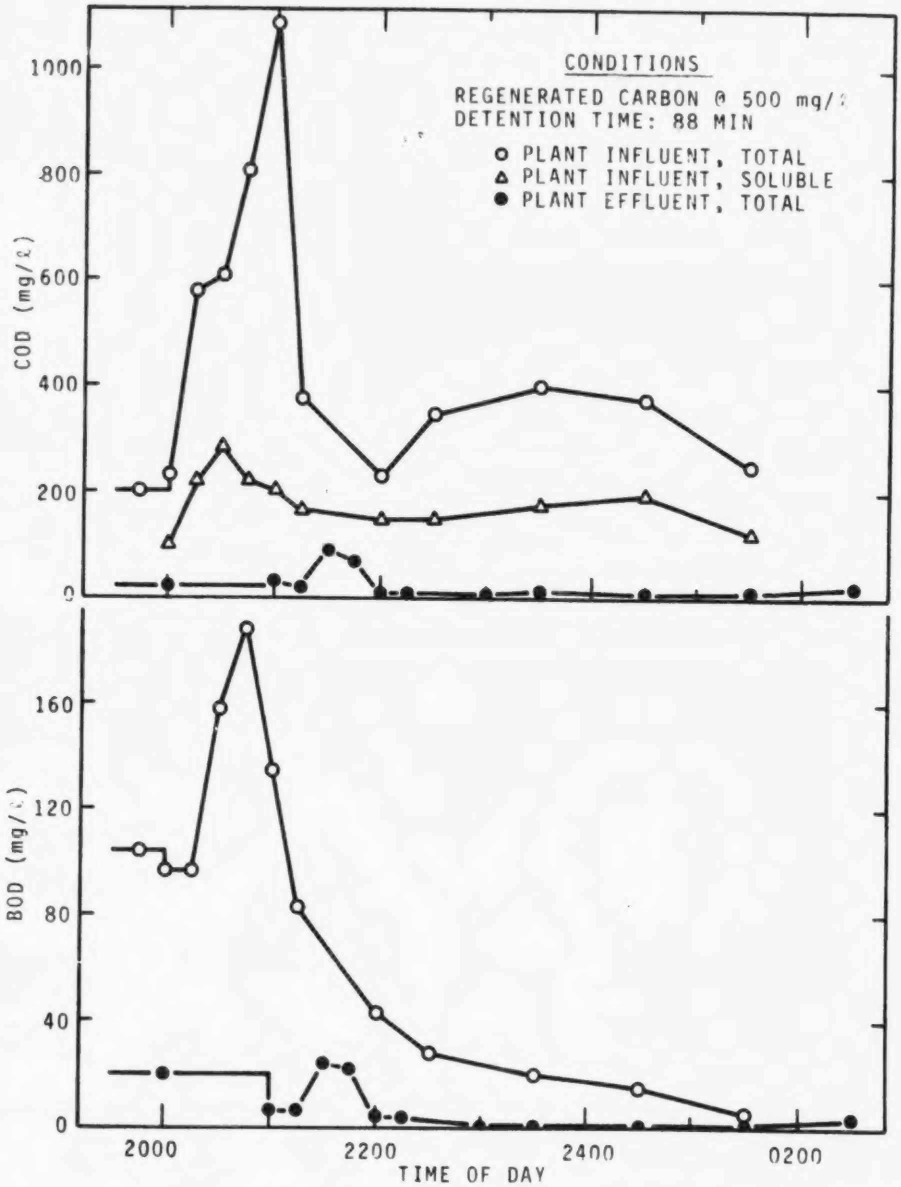


FIGURE 32. STORM EFFECT ON COD AND BOD - 5/16-17/72

These observations are supported by a series of jar tests which were run during the course of the 7/29/71 storm. Four samples collected during increasing, peak, decreasing and minimum solids loading periods were examined with the results presented in Figures 33 and 34. The data in these figures emphasize the important role of effective plant solids removal during a storm. The points corresponding to 0 carbon dose represent the unfiltered supernatant liquid after alum and polyelectrolyte treatment. A large portion of the total BOD and COD was removed without the use of carbon; in fact, at peak solids loading, over 90 percent of both BOD and COD were removed. However, even at this level of removal, a residual COD of 92 mg/l remained at the storm peak solids loading. Thus, alum coagulation alone is not sufficient to produce a low COD effluent. These jar test data suggest that as the storm progressed and the COD was increasing, a carbon dose of 600 mg/l was warranted to effect good COD removal. Once the storm peak was passed, however, the carbon dose could be reduced to the 200-300 mg/l level with virtually complete removal of all sorbable COD.

During the course of each of the storms, the suspended solids, COD, and BOD profiles of the wastewater followed the turbidity profile with the peaks of the curves usually occurring at the same time. In some instances, the BOD and/or COD tended to peak slightly ahead of the turbidity. It was noted that the soluble COD followed the same general pattern as the total COD. These observations suggest that turbidity can be used to monitor trend variations in other influent parameters as a storm progresses. A decrease in turbidity should be indicative of a corresponding decrease in soluble organics. Therefore, after the turbidity has peaked, it should be possible to effect virtually complete removal of sorbable organics at a substantially reduced carbon dose until the storm has subsided at which time normal operation could be resumed. Depending upon the effluent quality required and upon the wastewater characteristics at a particular site, it would be possible to operate the treatment process throughout storm periods at a much lower carbon dose than the 600 mg/l indicated for raw sewage treatment. Thus, operating economies could be introduced by operating at a low carbon dose for an entire storm period or by reducing the carbon dose after the peak organic loading had occurred. The second of these alternatives assures the highest effluent quality at the lowest cost.

Prior to the 9/13/71 and 9/16/71 storms, the New York State Department of Environmental Conservation installed a flowmeter in the sewer from which the plant influent was drawn. Therefore, it was decided to attempt to adjust the pilot plant flow rate to parallel the flow in the sewer during

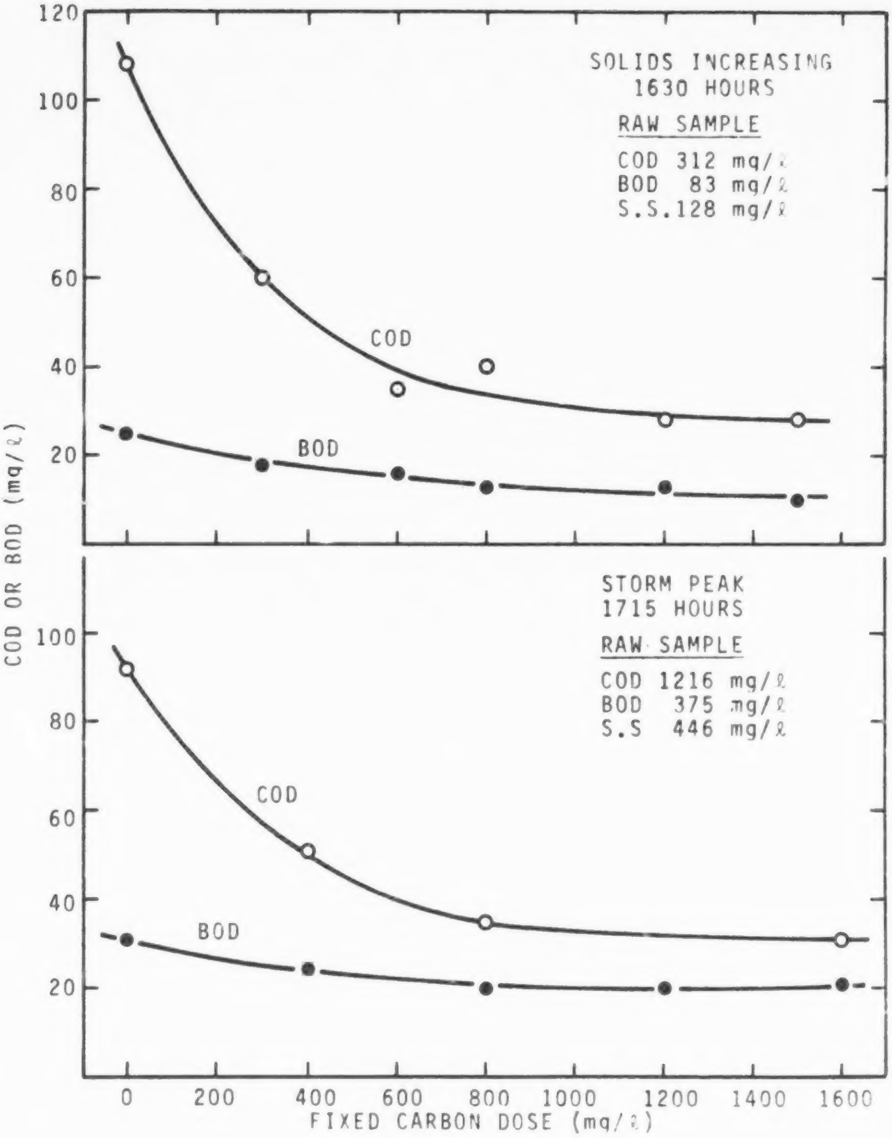


FIGURE 33. JAR TEST DETERMINATION OF CARBON REQUIREMENTS DURING INCREASING AND PEAK LOADING OF 7/29/71 STORM

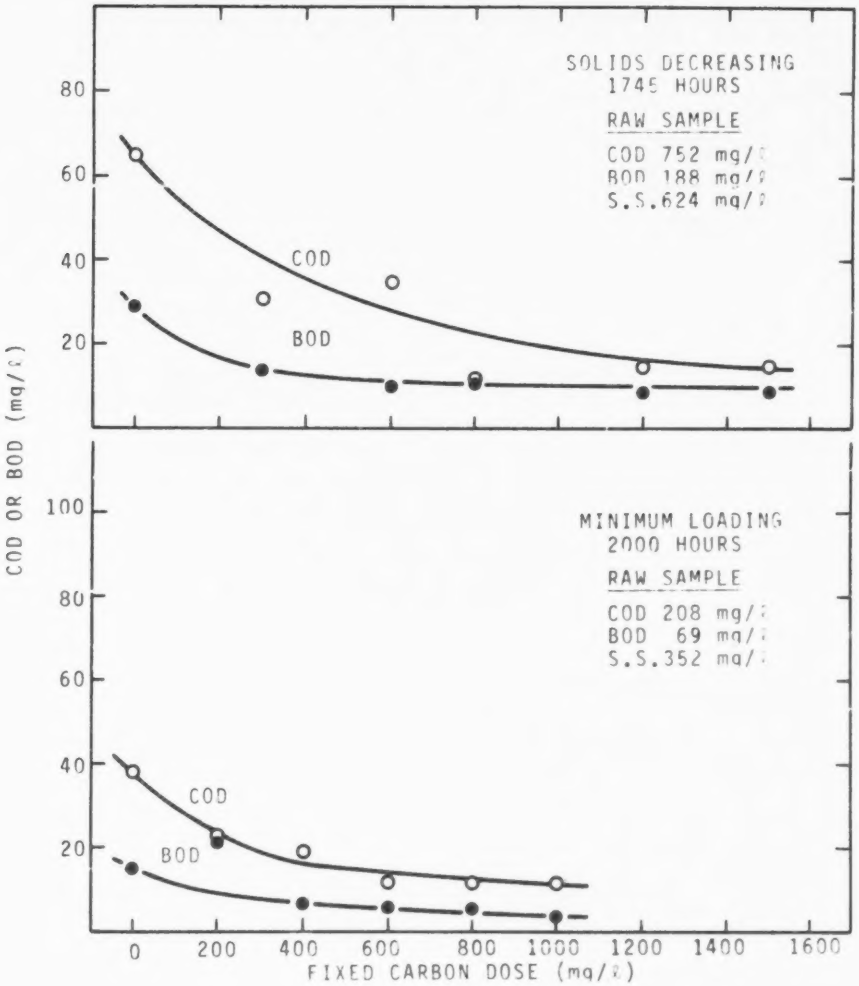


FIGURE 34. JAR TEST DETERMINATION OF CARBON REQUIREMENTS DURING DECREASING AND MINIMUM LOADING OF 7/29/71 STORM

subsequent storms. Attempts to accomplish this goal during the 9/13/71 and 9/16/71 storms were not completely successful. However, during the latter storm, the pilot plant flow rate, initially at 35 gpm, was increased to 75 gpm in less than two minutes during peak storm loading with no observable effluent quality deterioration or operational upsets. Thus, it appears that plant performance is highly insensitive to rapid changes in flow rate if chemical doses are rapidly adjusted to correspond to the increased flow.

Pilot plant operations have demonstrated that it is possible to produce a high quality product water from combined sewage in a total treatment time of 50 minutes. Moreover, the system can accommodate rapid changes in flow and composition. It appears feasible that a system based on this process could be highly automated. Carbon and chemical doses could be controlled on the basis of flow and/or turbidity monitoring to assure maximum system reliability with minimum chemical usage.

MUNICIPAL SEWAGE TREATMENT

During most of the 1971 campaign, grab samples of the plant influent and effluent were routinely collected at two hour intervals and composited over a twenty-four hour period of plant operation. Several determinations of the diurnal variations in influent and plant effluent quality were made during this portion of the program. Particular emphasis was placed on this approach during the period when regenerated carbon and reclaimed alum were in use. Plant operational data for the 1971 portion of the program are given in Tables 4 and 5 and the results are presented in Table 6 and in Figures 35-47.

The diurnal data showed BOD and COD peaks in the plant effluent which could not be explained by variations in influent quality or by operational upsets. These peaks are evident in the curve presented in Figure 37. Later runs in which the influent waste stream was sampled on an hourly basis, as in Figures 40, 42, 44, and 46, indicated rapid fluctuation in influent quality. High BOD and COD peaks of perhaps an hour's duration frequently occurred. These inordinately high COD peaks (as great as 5200 mg/l) appeared to occur on a fairly regular basis and were totally unexpected in a predominantly residential area presumably free of industrial wastes.

Observation of the highly variable nature of the influent quality at the Albany site suggested that the two hour samples composited over a twenty-four hour period might not be completely representative of the waste stream. Reexamination of

TABLE 4

PLANT OPERATIONAL DATA FOR 1971 STUDIES USING VIRGIN CARBON

Date	Wastewater Flowrate (gpm)	Detention Time (min)	Polyelectrolyte Dose (mg/l)	Carbon Dose (mg/l)	Carbon Type
6-7-71	40	88	6.0	800	Aqua Nuchar
8	40	88	6.0	800	Aqua Nuchar
9	40	88	4.0	1000	Aqua Nuchar
10	40	88	4.0	1000	Aqua Nuchar
14	40	88	2.0	1000	Aqua Nuchar
15	40	88	2.0	1000	Aqua Nuchar
16	40	88	2.0	1000	Aqua Nuchar
17	40	88	2.0	800	Aqua Nuchar
21	40	88	2.0	400	Darco XPC
28	40	88	2.0	800	Darco XPC
7-21-71	40	88	2.0	1170	Darco XPC
13	40	88	2.0	1330	Darco XPC
14	40	88	2.0	1180	Darco XPC
15	72	44	2.2	865	Darco XPC
16	72	44	2.0	800	Darco XPC
19	70	45	2.0	625	Darco XPC
21	70	45	1.5	800	Darco XPC
22	73	44	1.7	800	Darco XPC
26	69	45	1.2	630	Darco XPC
27	70	45	2.0	790	Darco XPC
8-11-71	41	86	3.5	550	Aqua Nuchar
25	43	82	2.6	590	Aqua Nuchar
26	45	78	2.7	486	Aqua Nuchar
30	72	44	2.8	573	Aqua Nuchar
9-1-71	64	55	2.5	950	Aqua Nuchar
2	62	57	2.7	880	Aqua Nuchar
9	70	45	2.9	950	Aqua Nuchar

TABLE 5

PLANT OPERATIONAL DATA FOR DIURNAL STUDIES

Date	Detention Time (min)	Carbon Dose (mg/l)	Lime Dose (mg/l)	Acid Usage (lb/lbC)	Carbon Type
7/12-13/71	88	1170	--	--	Darco XPC
7/14-15/71	88	1190	--	--	Darco XPC
8/17-18/71	112	550	119	0.32	Aqua Nuchar
9/28-29/71	50	656	165	0.64	Regenerated
10/4-5/71	50	482	220	0.91	Regenerated
10/7-8/71	50	357	178	0.57	Regenerated
10/13-14/71	50	440	248	0.66	Regenerated
10/18-19/71	50	440	194	0.43	Aqua Nuchar
10/25-26/71	50	537	171	0.67	Regenerated
4/14-19/72	50	621	237	0.48	Aqua Nuchar
4/24-26/72	88	657	140	0.59	Regenerated
5/1-10/72	88	601	165	0.60	Regenerated
5/15/23/72	88	506	213	0.76	Regenerated
6/7-12/72	88	570	226	0.62	Regenerated
6/13-15/72	88	632	203	0.74	Regenerated
6/16/72	88	640	182	0.65	Regenerated

TABLE 6

Plant Performance Data During
1971 Operations Using Virgin Carbon

Date	COD (mg/l)		BOD (mg/l)		SS (mg/l)	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
6-7-71	400	35	113	32	192	21
8	238	28	90	27	62	21
9	442	46	96	17	73	5
10	365	28	--	--	135	10
14	280	52	--	--	86	8
15	270	50	89	6	92	3
16	355	40	99	13	102	7
17	228	34	91	17	108	9
21	448	68	150	25	152	4
28	114	20	50	6	128	3
7-12-71	340	36	120	20	206	5
13	265	35	96	20	73	10
14	220	30	78	19	72	3
15	258	40	47	7	70	4
16	399	25	--	--	94	4
19	254	12	108	4	416	3
21	96	12	32	7	--	--
22	346	31	101	14	102	9
26	119	24	46	5	63	4
27	268	20	107	15	106	3
8-11-71	195	55	72	29	43	6
25	235	45	105	18	106	4
26	233	19	122	25	98	7
30	269	38	129	15	78	24
9-1-71	210	45	105	28	104	29
2	217	27	82	20	78	12
9	242	50	107	25	99	6

Note: Samples were composited over 24 hr periods from grab samples at 2 hr intervals

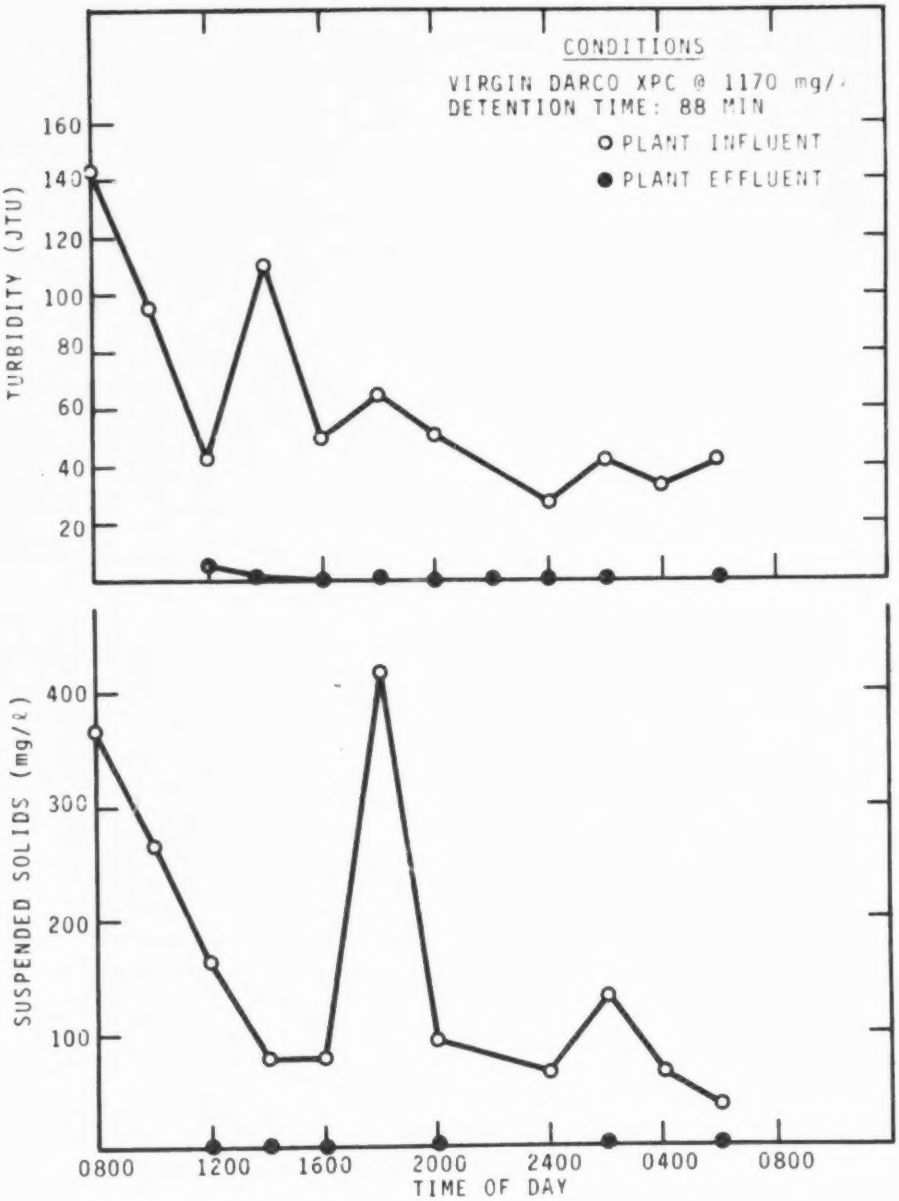


FIGURE 35. PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL 7/12-13/71

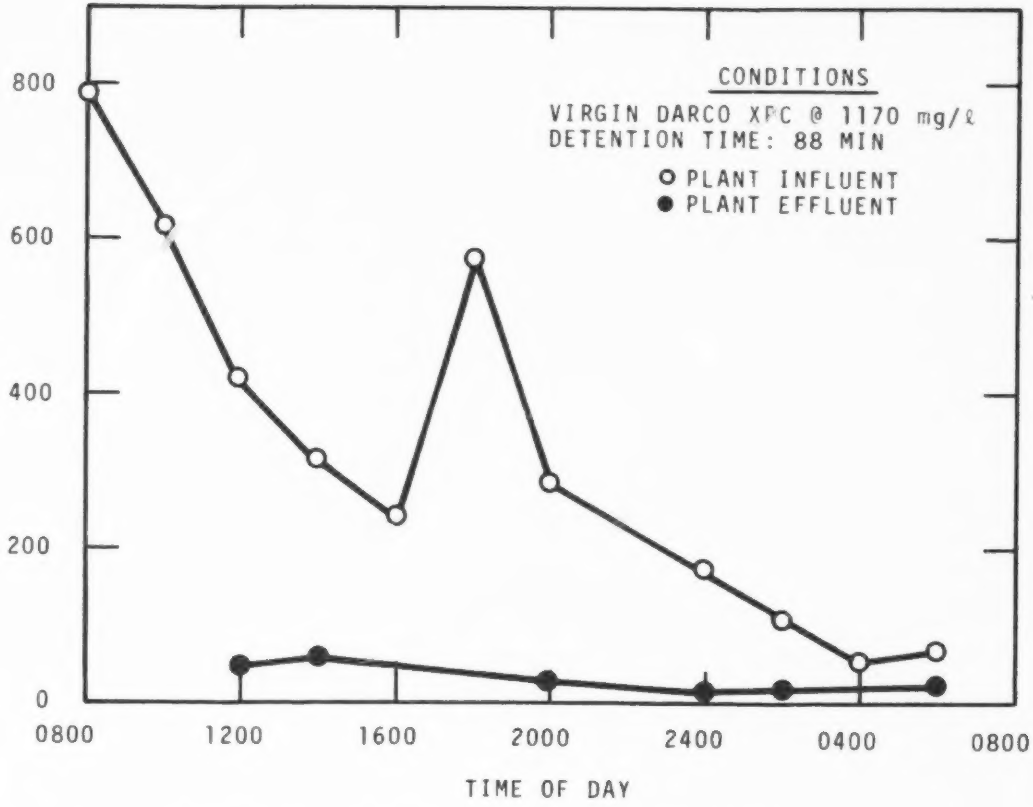


FIGURE 36. PLANT COD REMOVAL 7/12-13/71

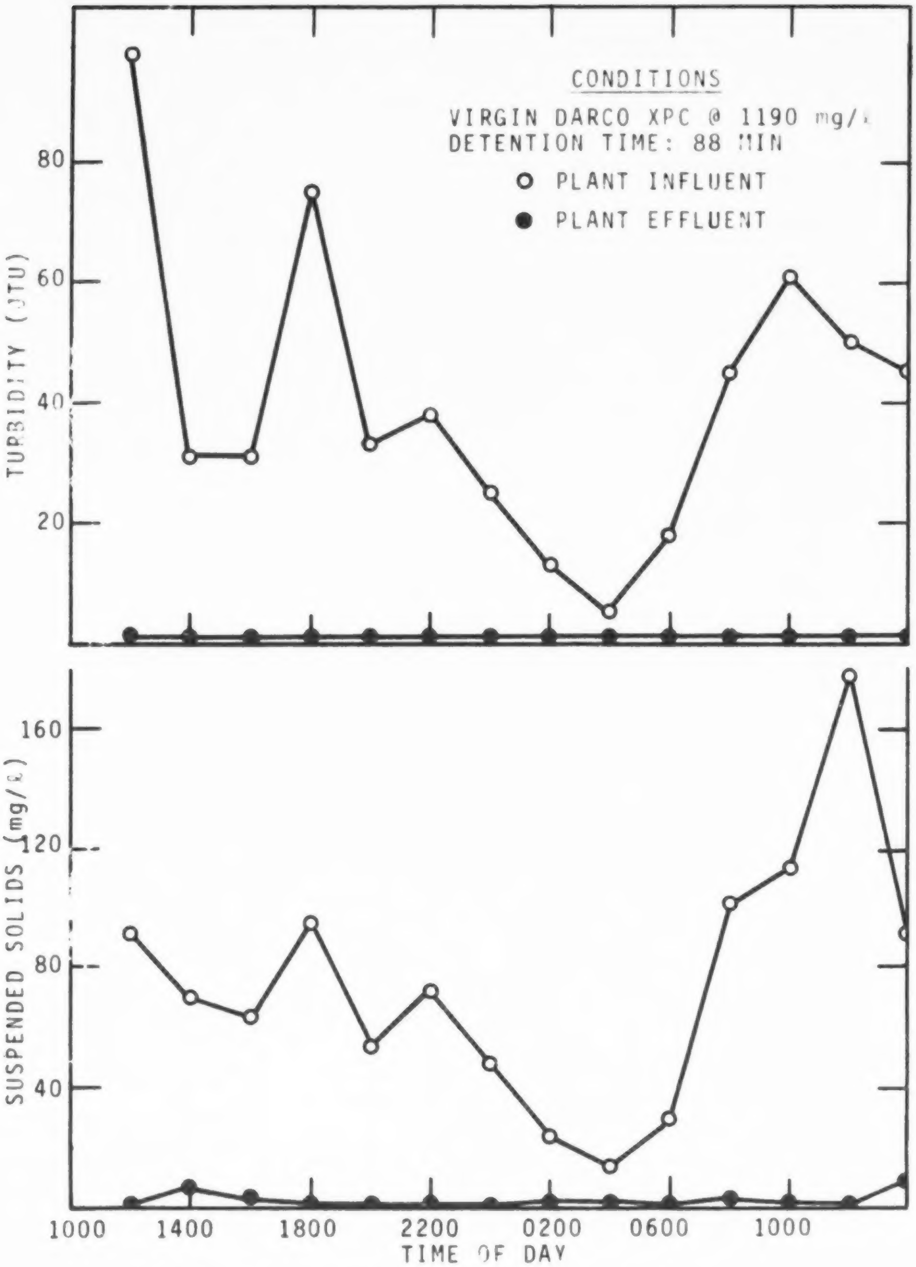


FIGURE 37. PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 7/14-15/71

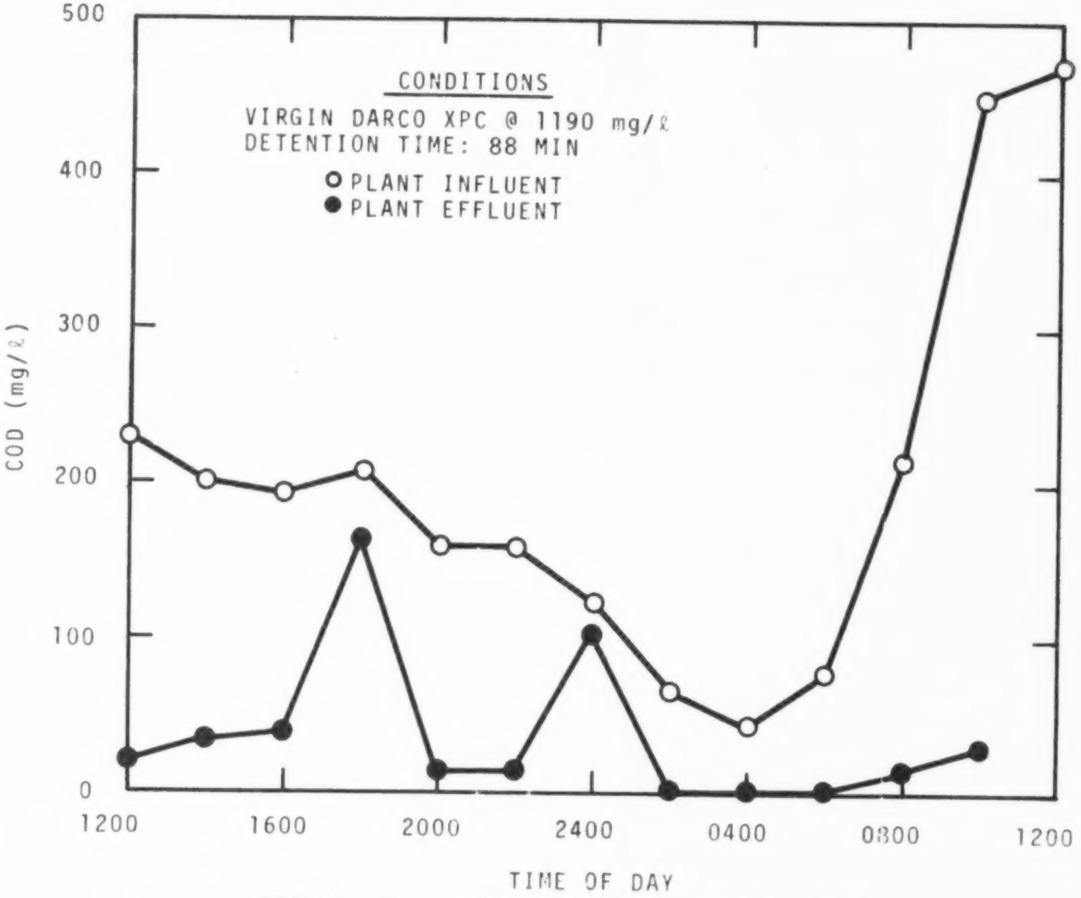


FIGURE 38. PLANT COD REMOVAL 7/14-15/71

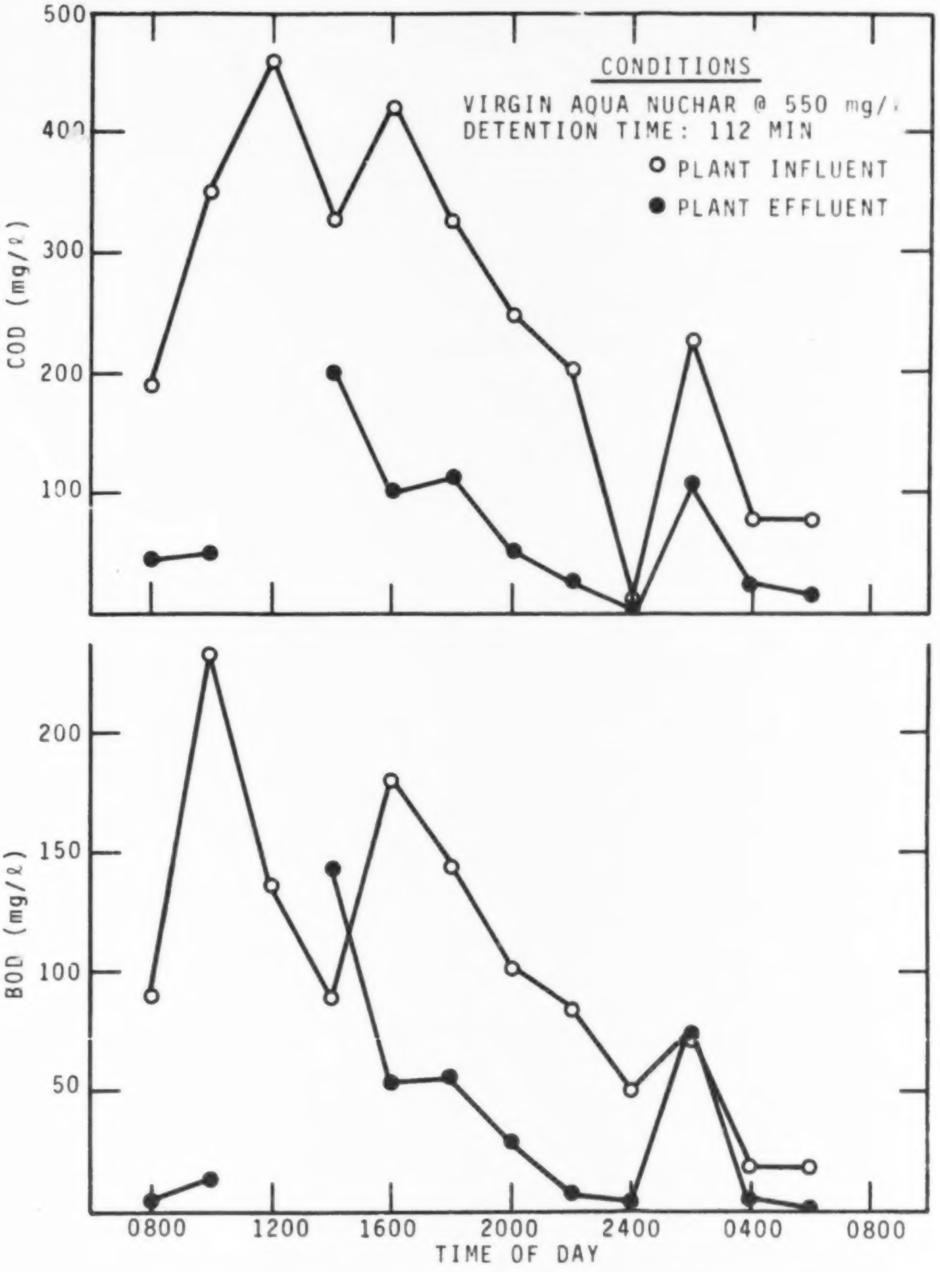


FIGURE 39. PLANT COD AND BOD REMOVAL 8/17-18/71

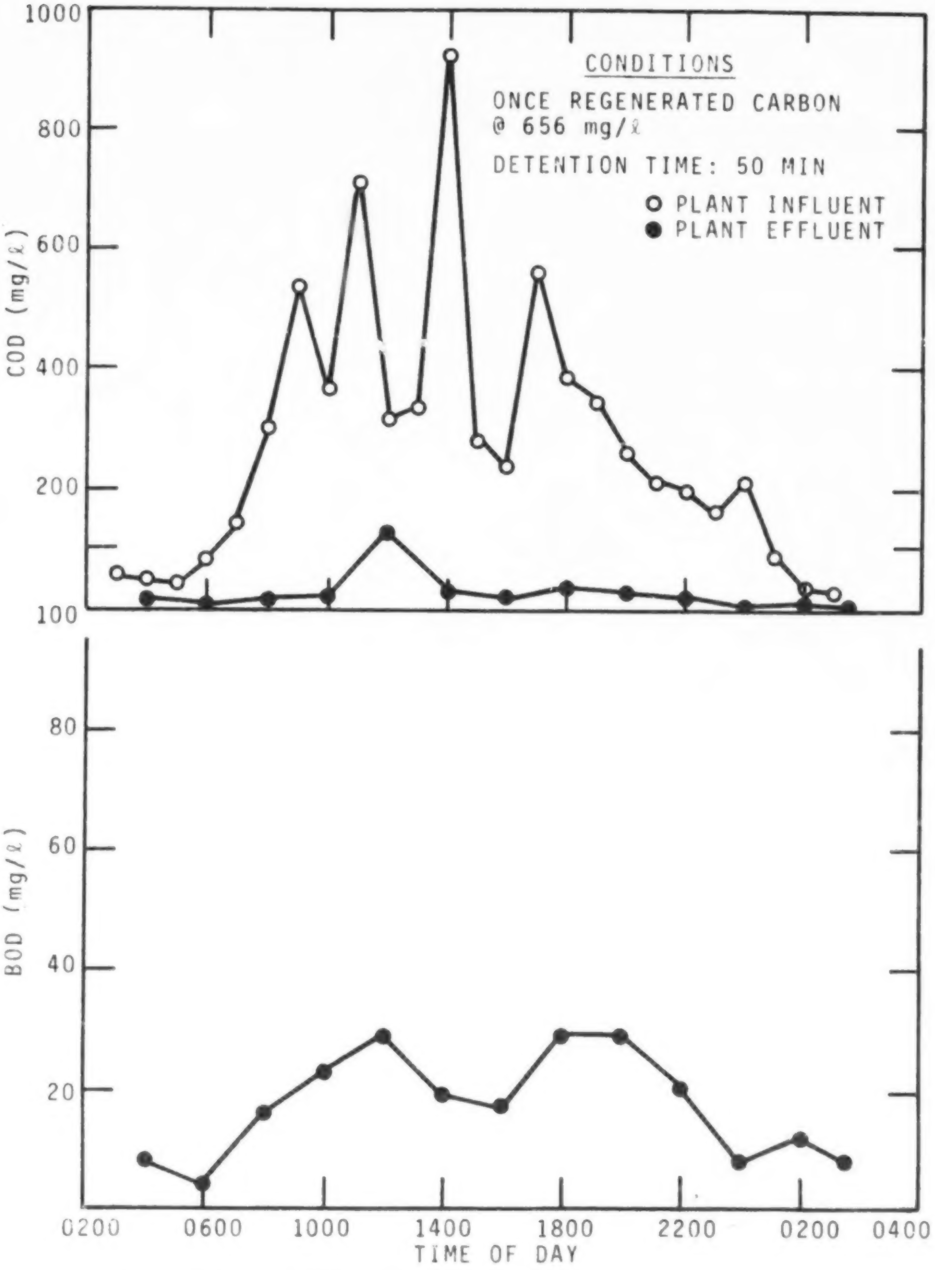


FIGURE 40. PLANT COD AND BOD REMOVAL 9/28-29/71

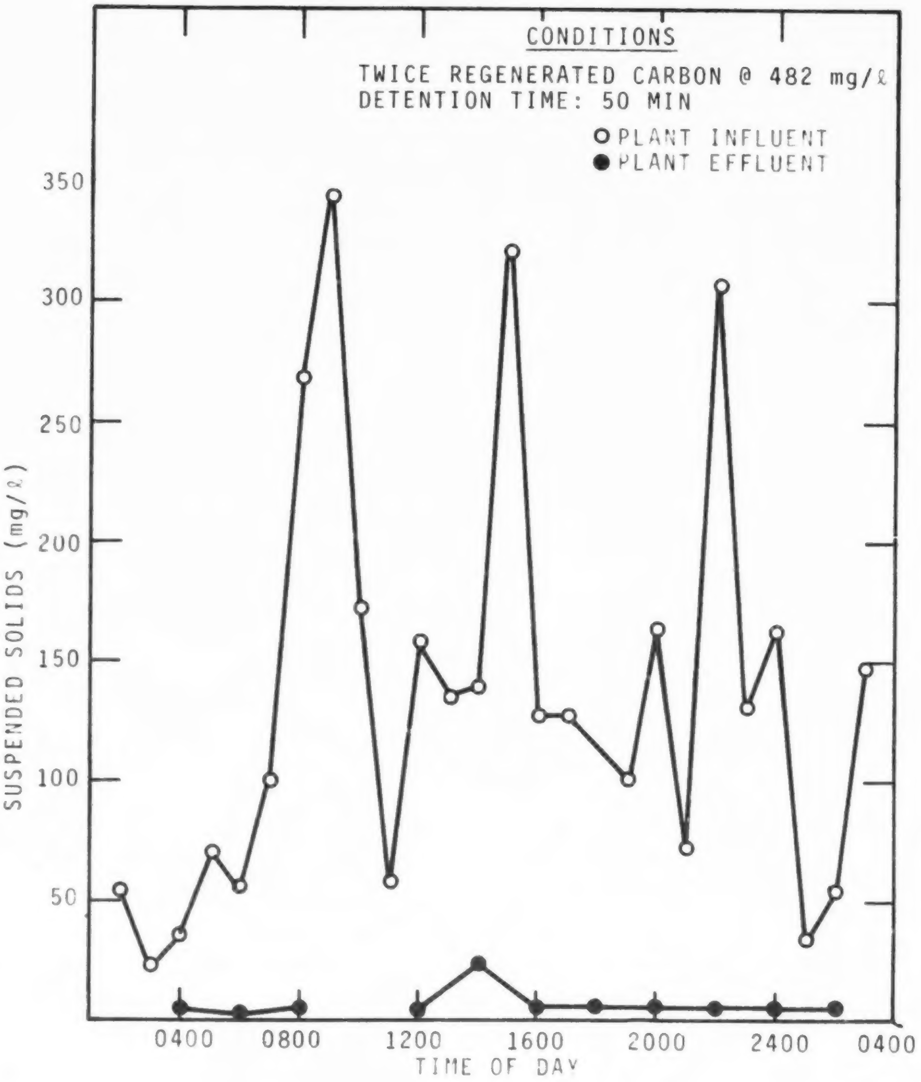


FIGURE 41. PLANT SUSPENDED SOLIDS REMOVAL 10/4-5/71

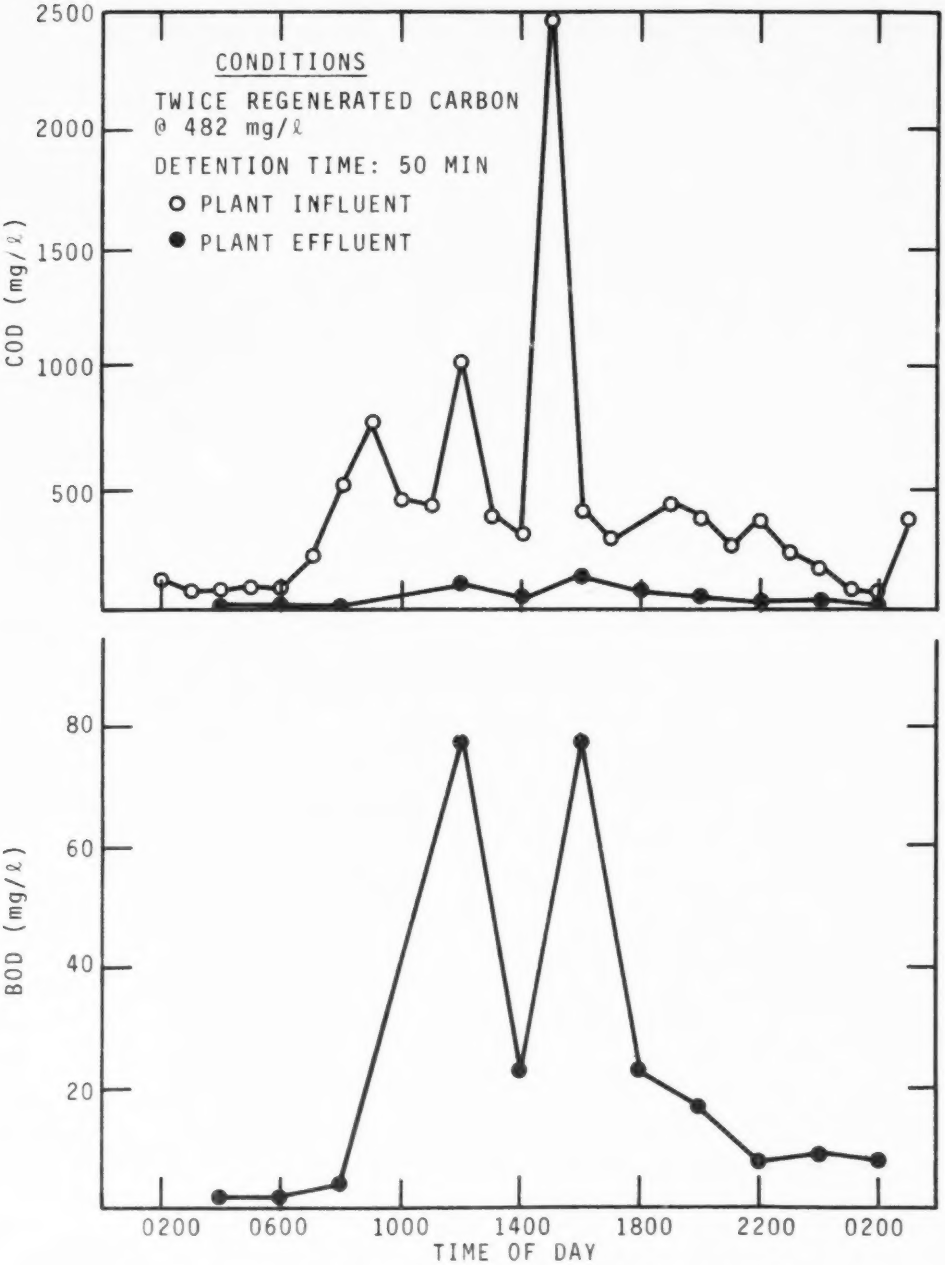


FIGURE 42. PLANT COD AND BOD REMOVAL 10/4-5/71

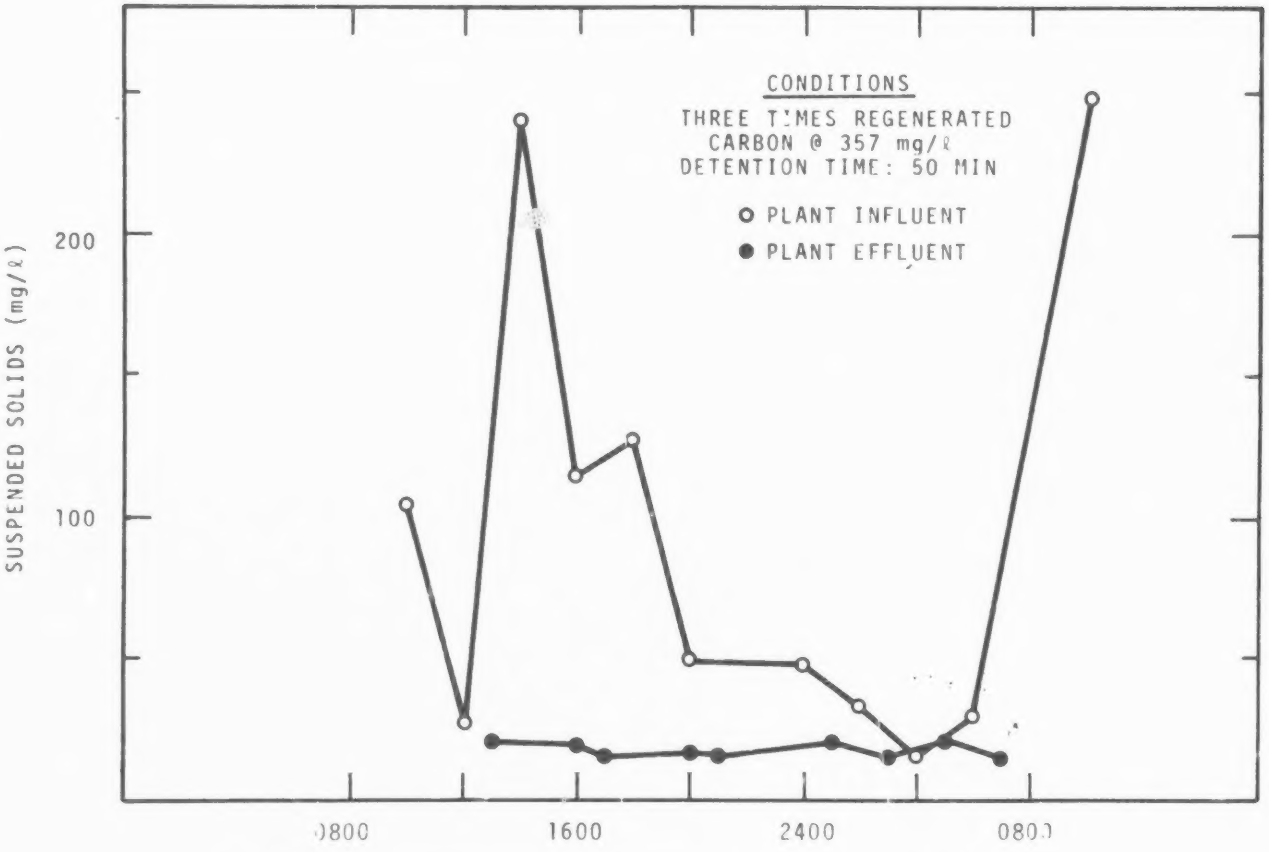


FIGURE 43. PLANT SUSPENDED SOLIDS REMOVAL 10/7-8/71

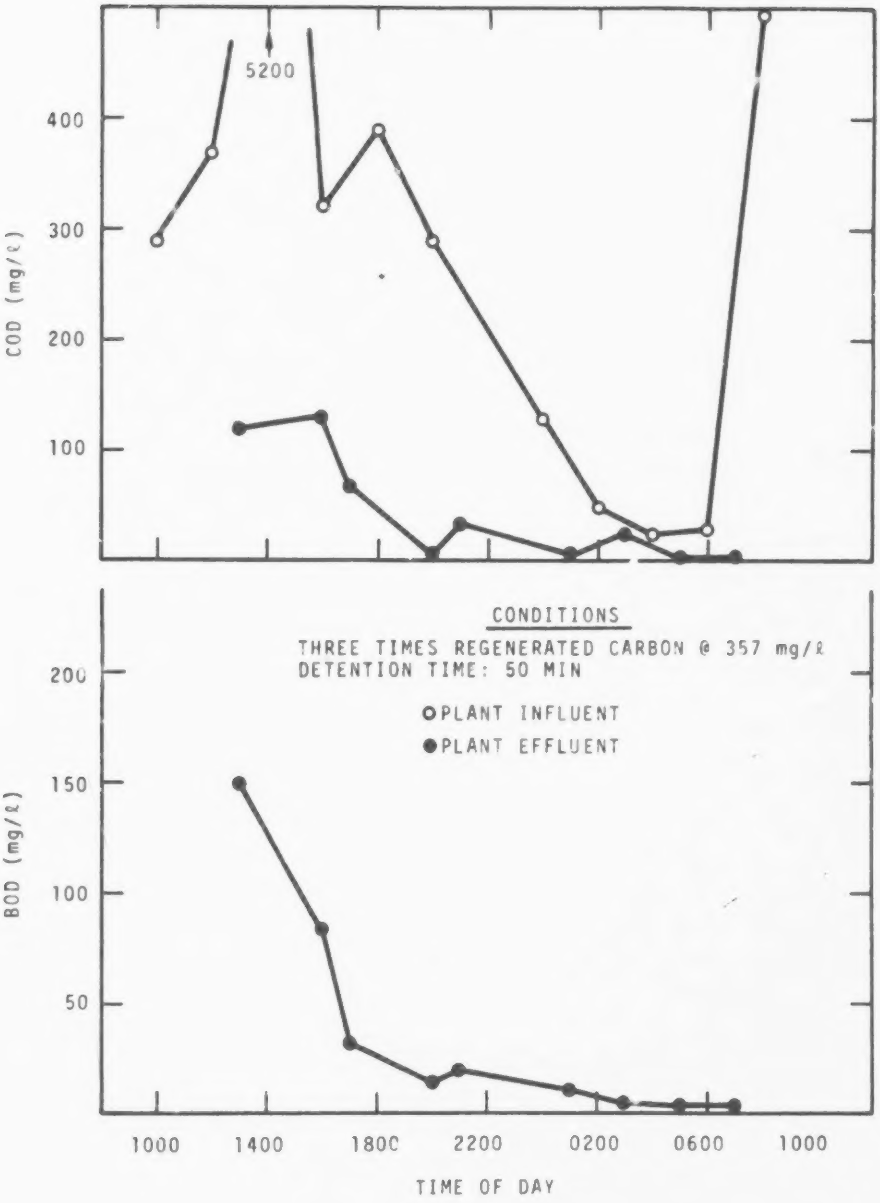


FIGURE 44. PLANT COD AND BOD REMOVAL 10/7-8/71

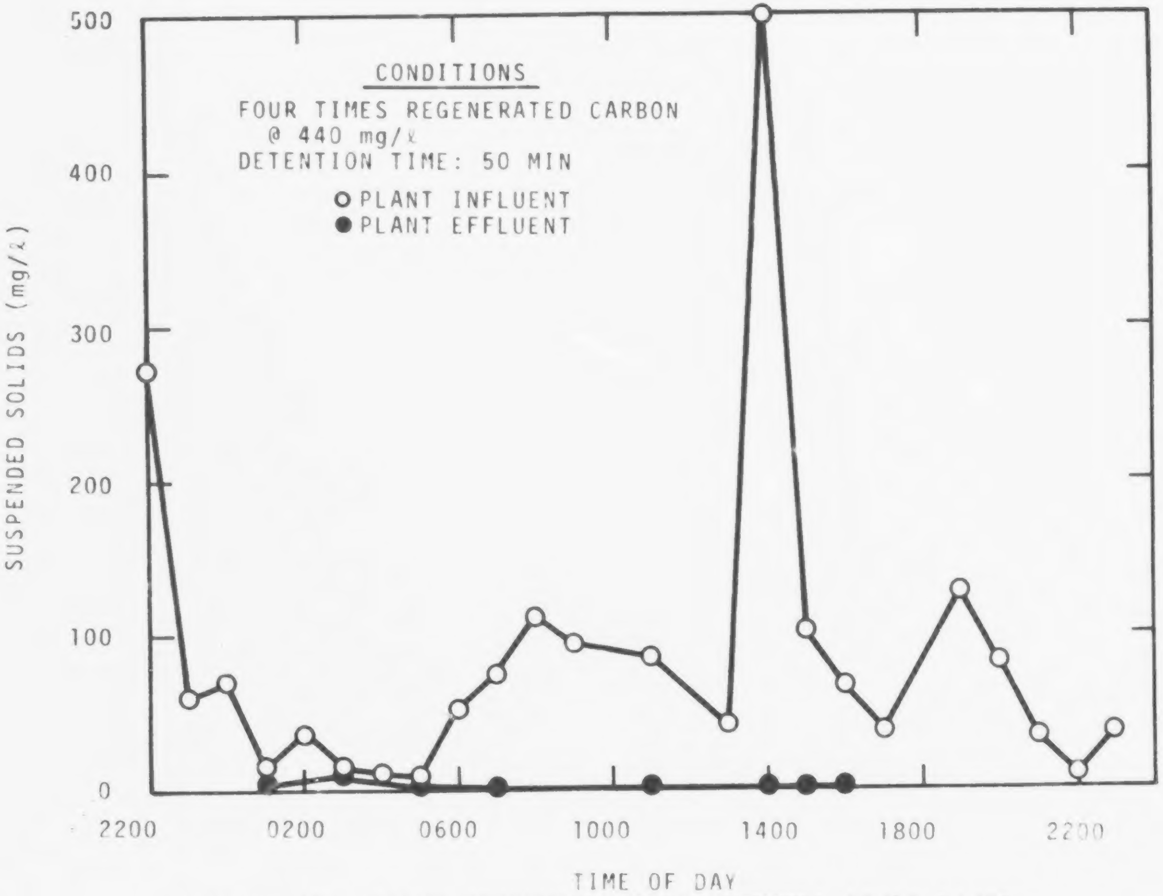


FIGURE 45. PLANT SUSPENDED SOLIDS REMOVAL 10/13-14/71

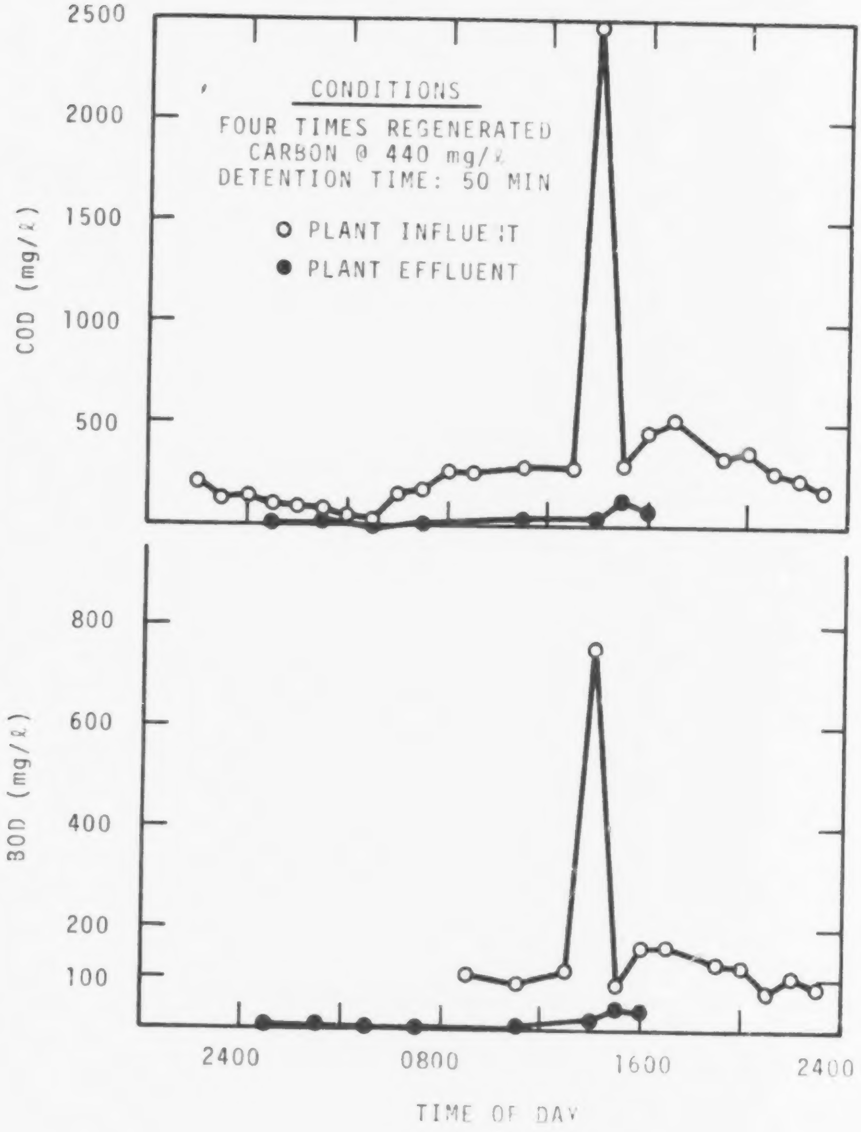


FIGURE 46. PLANT COD AND BOD REMOVAL 10/13-14/71

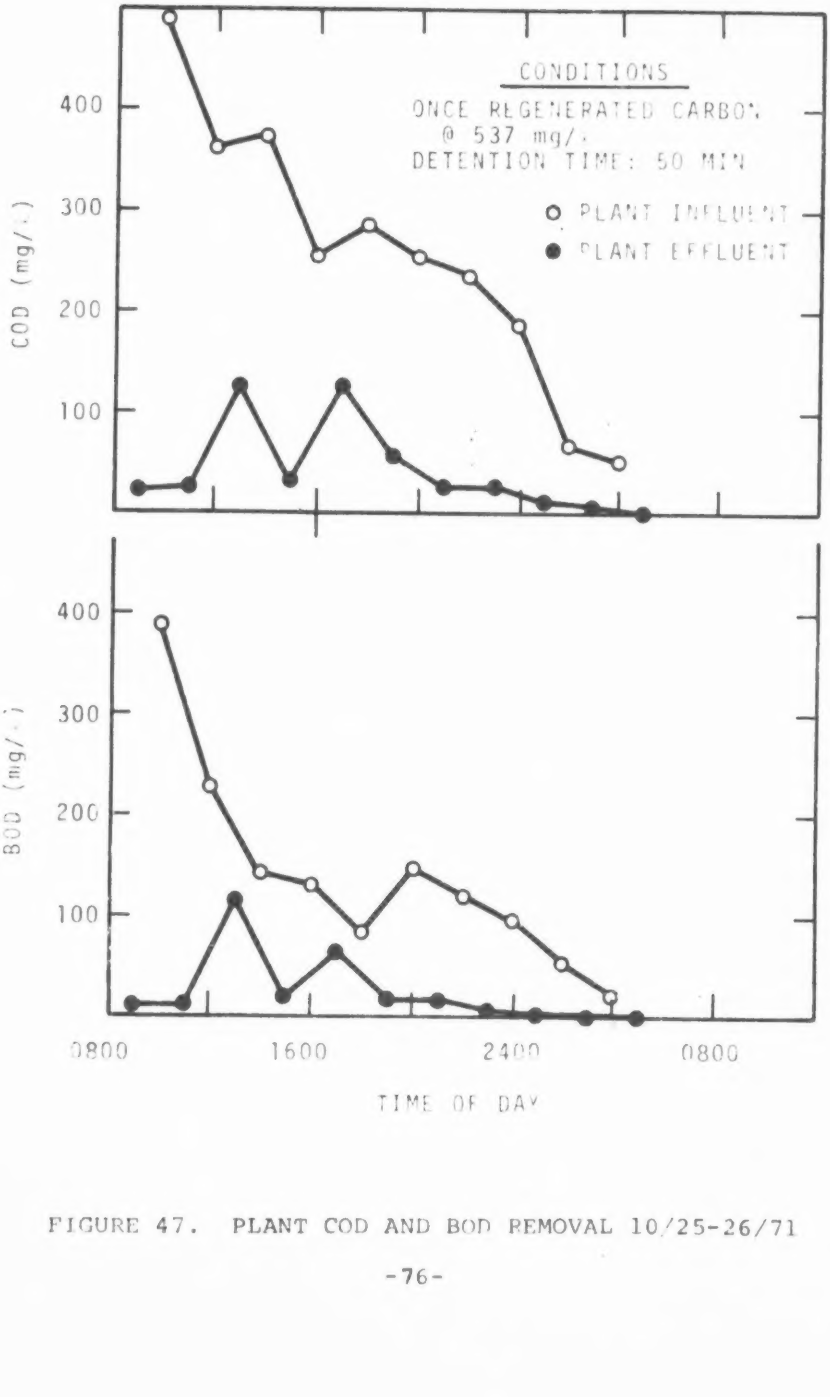


FIGURE 47. PLANT COD AND BOD REMOVAL 10/25-26/71

the data compiled on the two hour sampling schedule indicated that it was highly probable that the high COD peaks were frequently missed in the influent samples. On the other hand, these peak loadings tended to spread out over a longer period of time in the pilot plant and had an influence on effluent quality for a 2 to 3 hour interval. Therefore, they were detected in the effluent samples. Thus, the net result of missing the high influent BOD and COD peaks should have been to make the plant performance (on a percent removal basis) appear somewhat poorer than was actually the case.

Average plant effluent BOD, COD, and suspended solids concentrations for the 1971 studies were 17.8, 35, and 7.7 mg/l respectively. This represents removals of 82.3 percent BOD, 87.3 percent COD, and 94 percent suspended solids.

Prior to the start of the 1972 operations, an automatic sampling system which continuously composited influent and effluent samples for one or two hour sampling periods was installed. Data collected in this manner confirmed the high variability of the sewage strength. Although the COD peaks observed in the 1971 data were much subdued due to the averaging quality of the composite samples they were nevertheless present. Examination of the data shows that the plant effluent quality significantly deteriorates following these peak COD loadings.

Plant operational data for the 1972 studies are given in Table 5 and performance data are presented in Figures 48-59. In general, results were comparable to those observed in the 1971 portion of the program. During the 1972 operations the average effluent turbidity, suspended solids, COD, and BOD concentrations were 0.67 JTU, 3.1 mg/l, 39 mg/l, and 17 mg/l, respectively. This represents average removals of 98.1 percent suspended solids, 82.6 percent COD, and 81.3 percent BOD.

Effluent quality frequency distribution curves for BOD, COD, and suspended solids for the diurnal pilot plant operation in Albany are given in Figure 60. Figure 61 contains removal probability curves based on the pilot plant data for these same parameters.

Data from the pilot studies indicate that at times there was a significant non-adsorbable organic component present in the wastewater at the Albany site. When present, this non-adsorbable fraction represented BOD and COD residual of 10-20 mg/l and 20-50 mg/l, respectively, which could not be removed even at carbon doses as high as 1000 mg/l.

A significant non-adsorbable fraction was not detected in the Richland, Washington studies with powdered carbon nor in

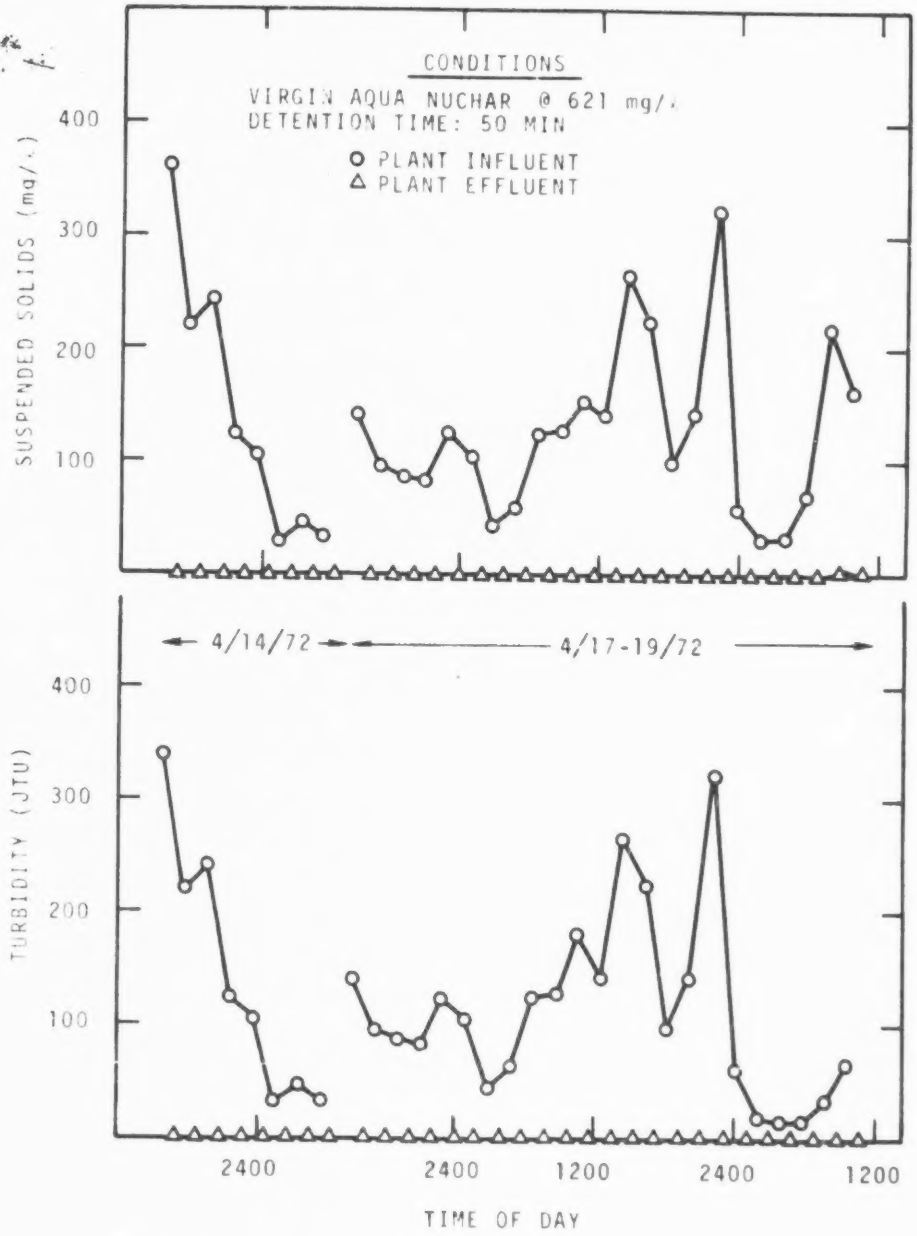


FIGURE 48. PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL - 4/14 & 4/17-19/72

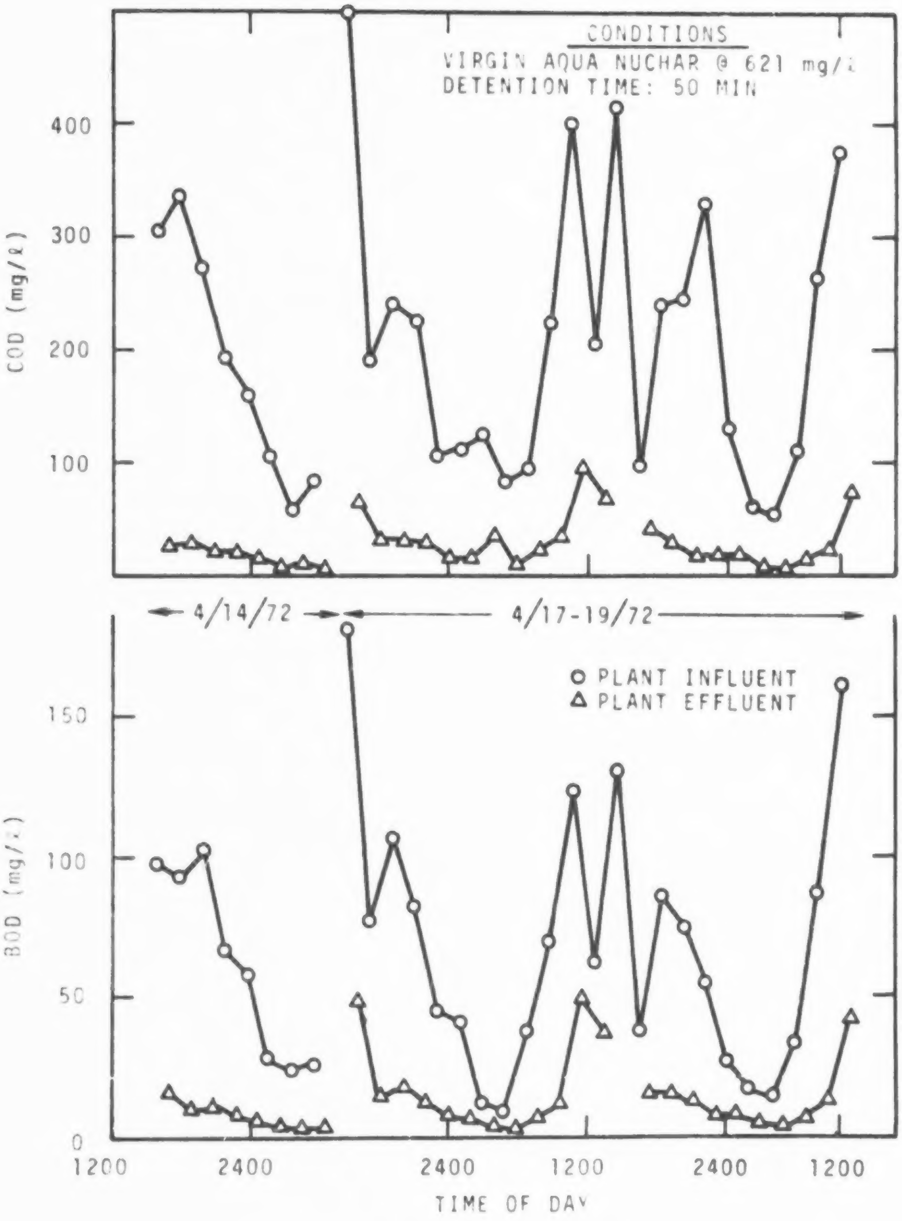


FIGURE 49. PLANT COD AND BOD REMOVAL
4/14 and 4/17-19/72

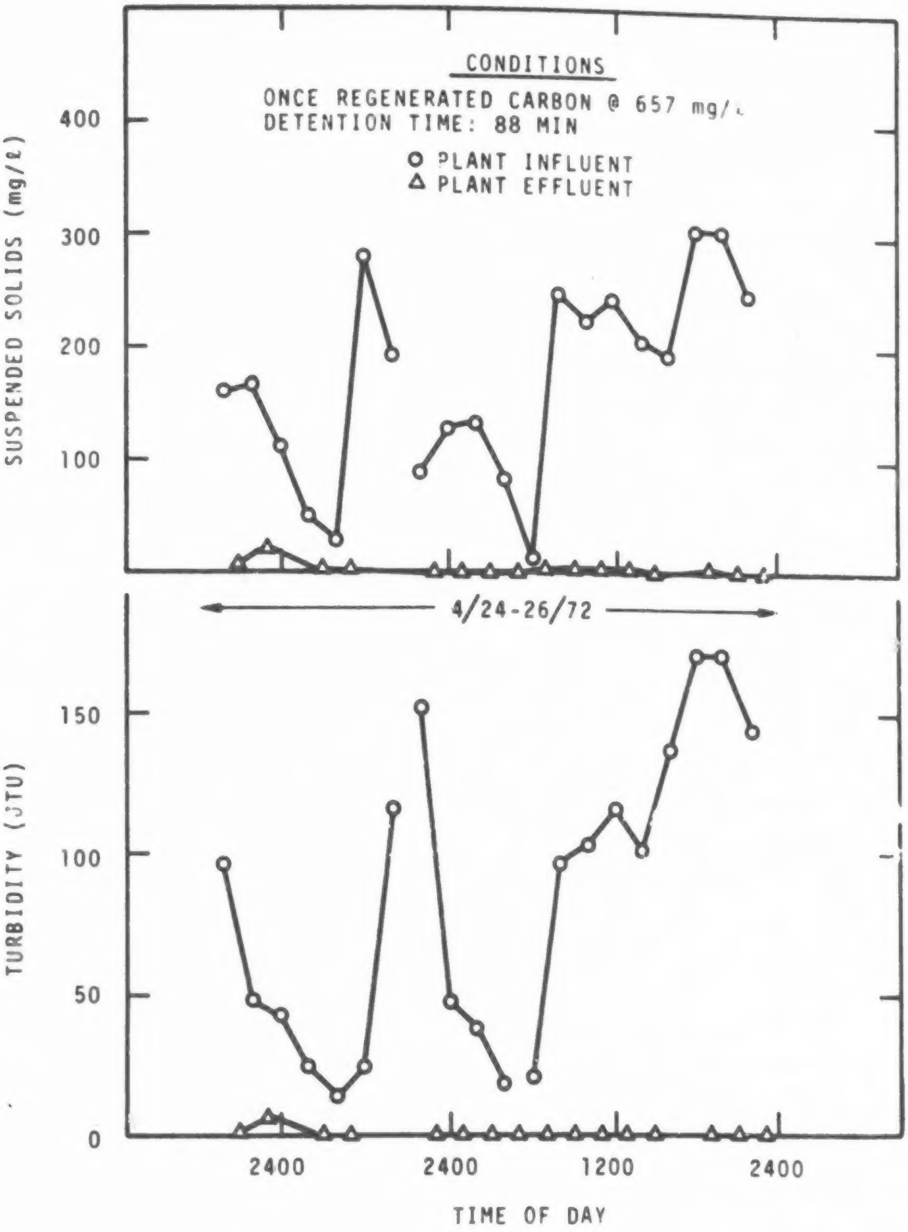


FIGURE 50. PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL 4/24-26/72

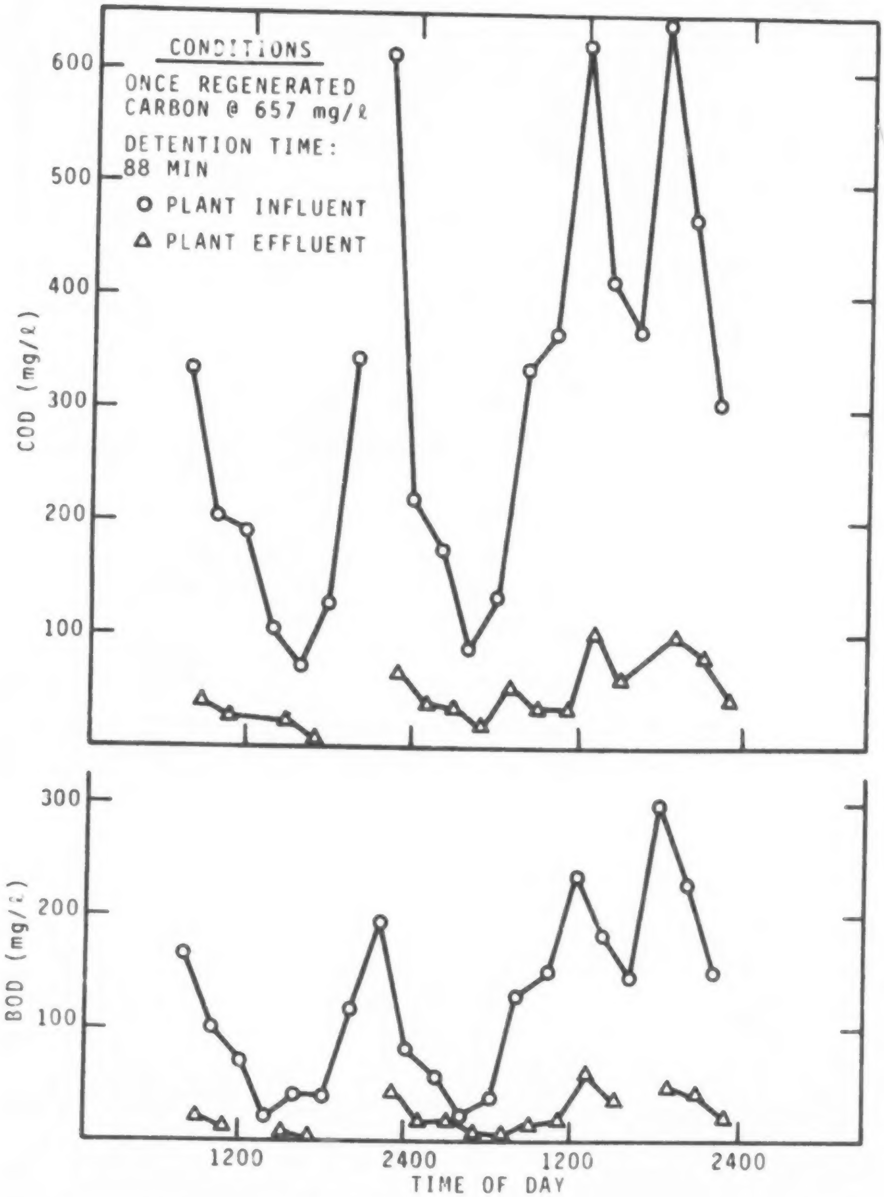


FIGURE 51. PLANT COD AND BOD REMOVAL 4/24-26/72

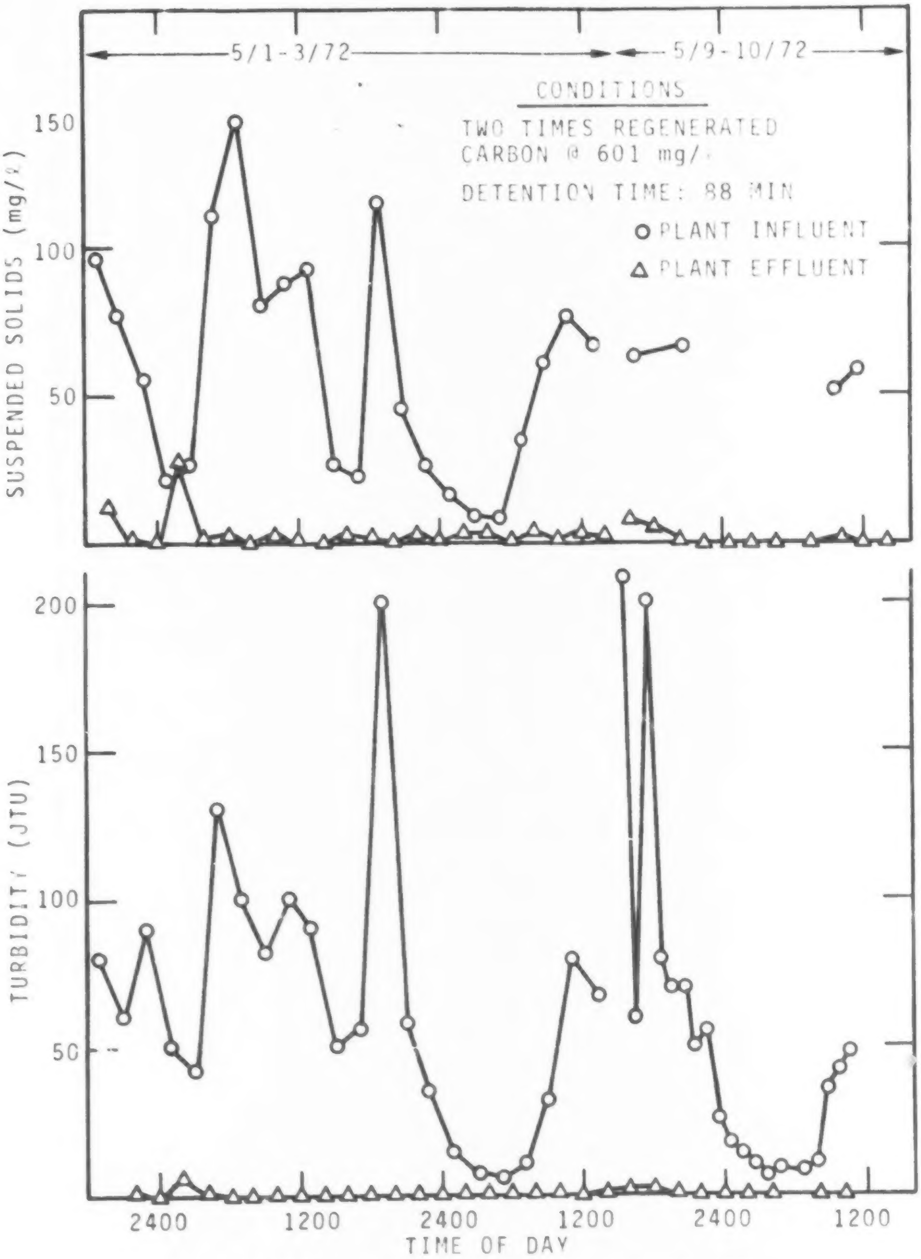


FIGURE 52. PLANT SUSPENDED SOLIDS AND TURBIDITY REMOVAL 5/1-3/72 & 5/9-10/72

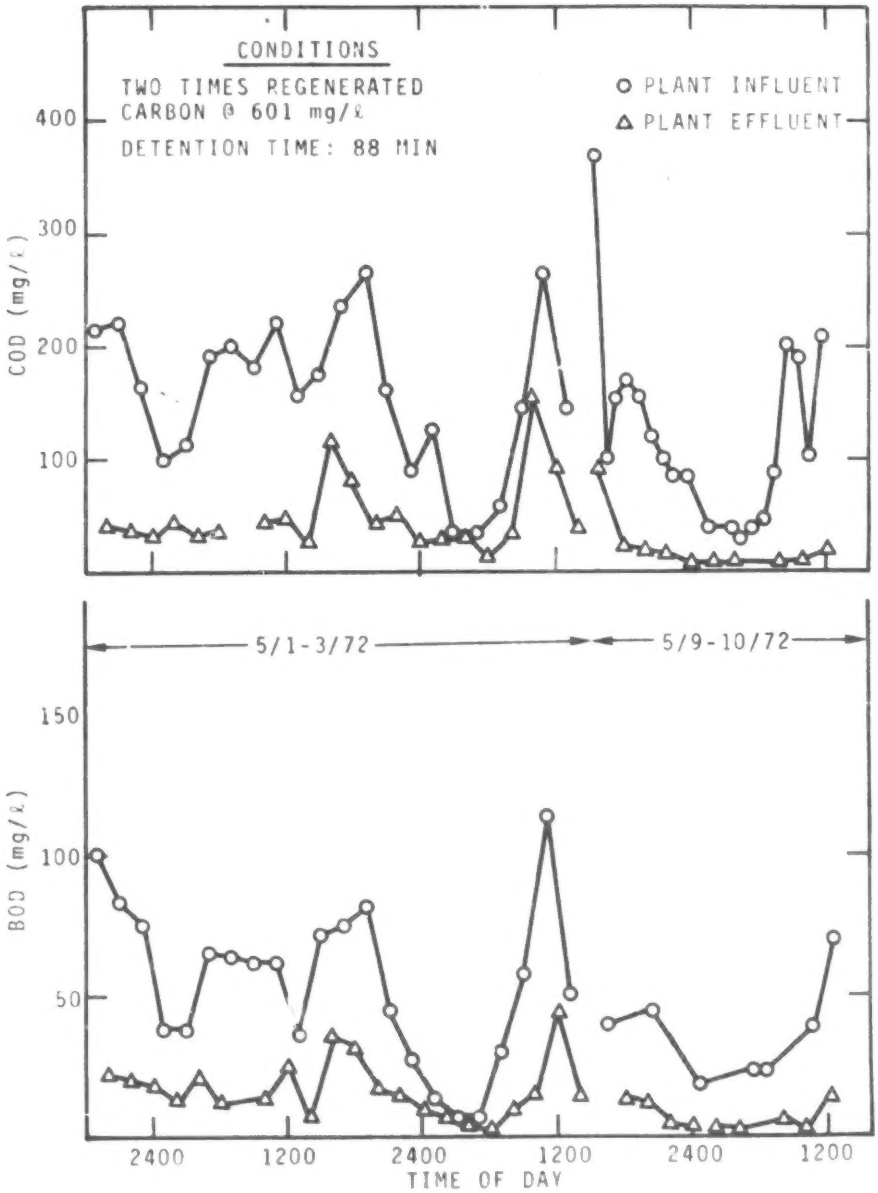


FIGURE 53. PLANT COD AND BOD REMOVAL
5/1-3/72 and 5/9-10/72

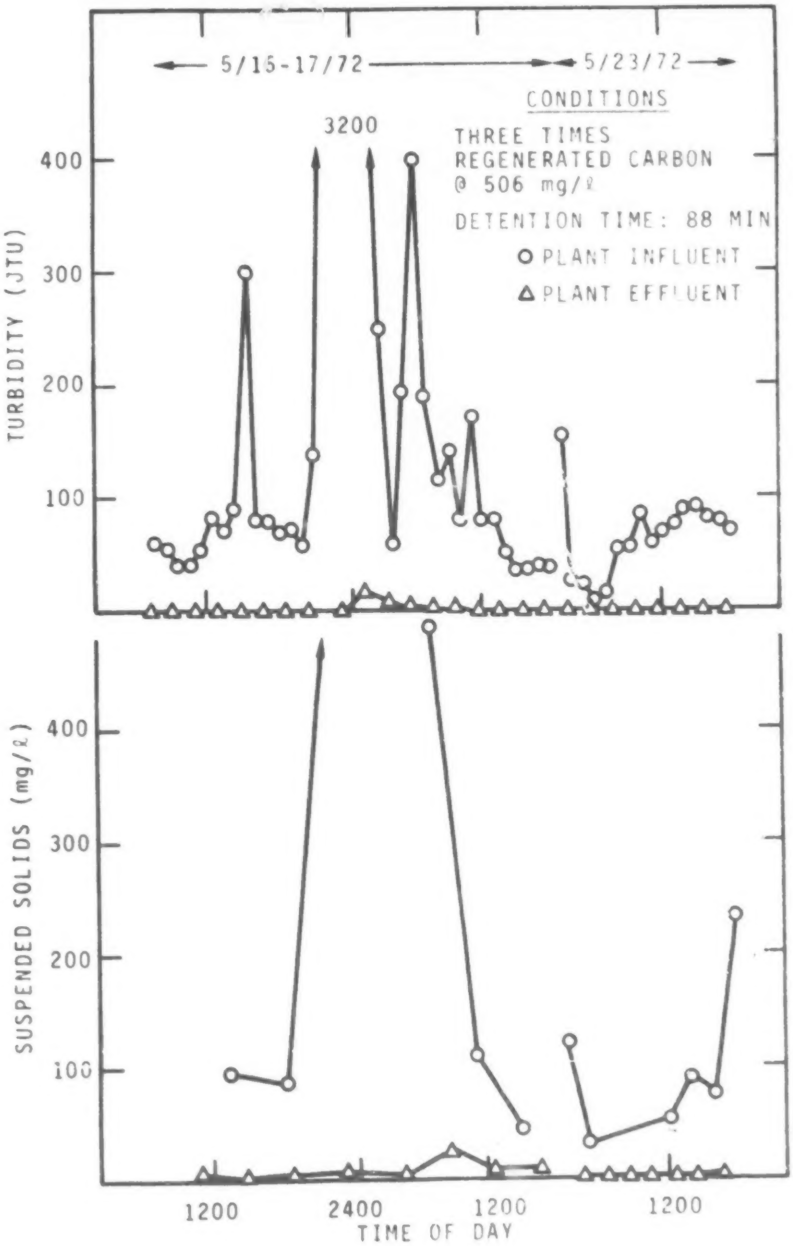


FIGURE 54. PLANT TURBIDITY AND SUSPENDED SOLIDS REMOVAL 5/16-17/72 & 5/23/72

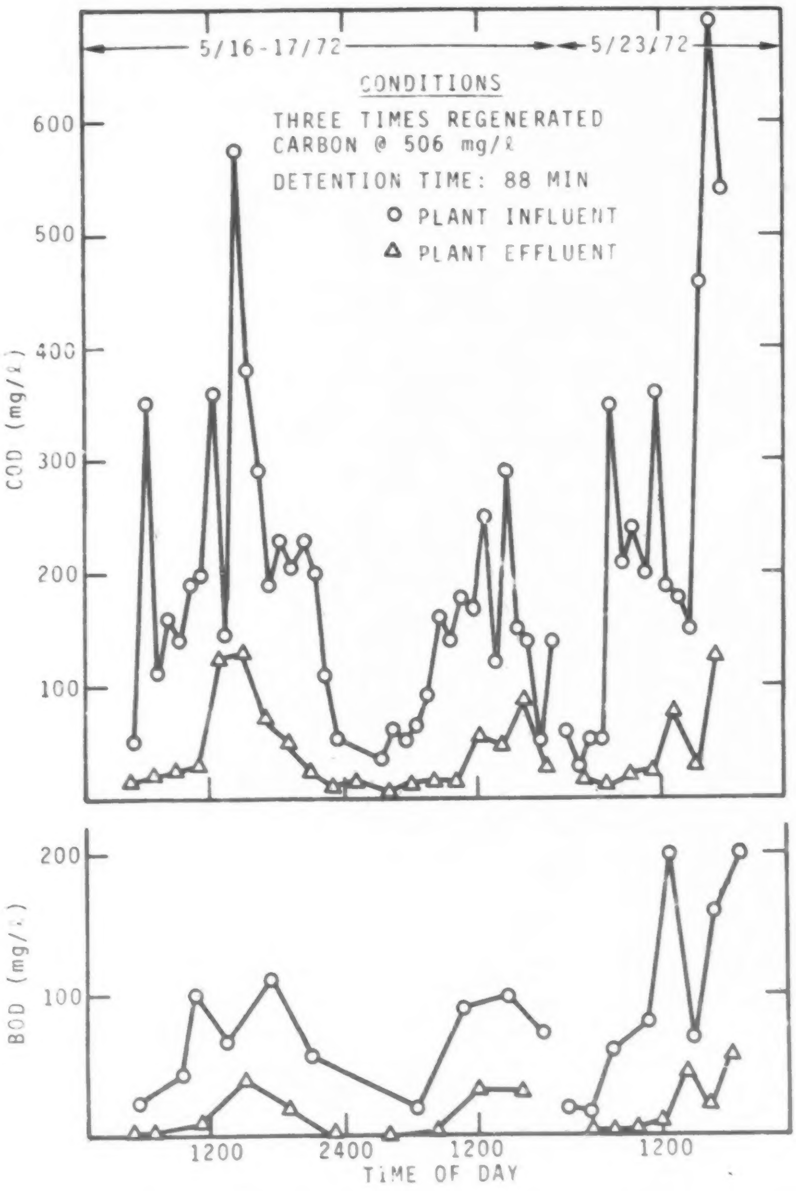


FIGURE 55. PLANT COD AND BOD REMOVAL 5/16-17/72 and 5/23/72

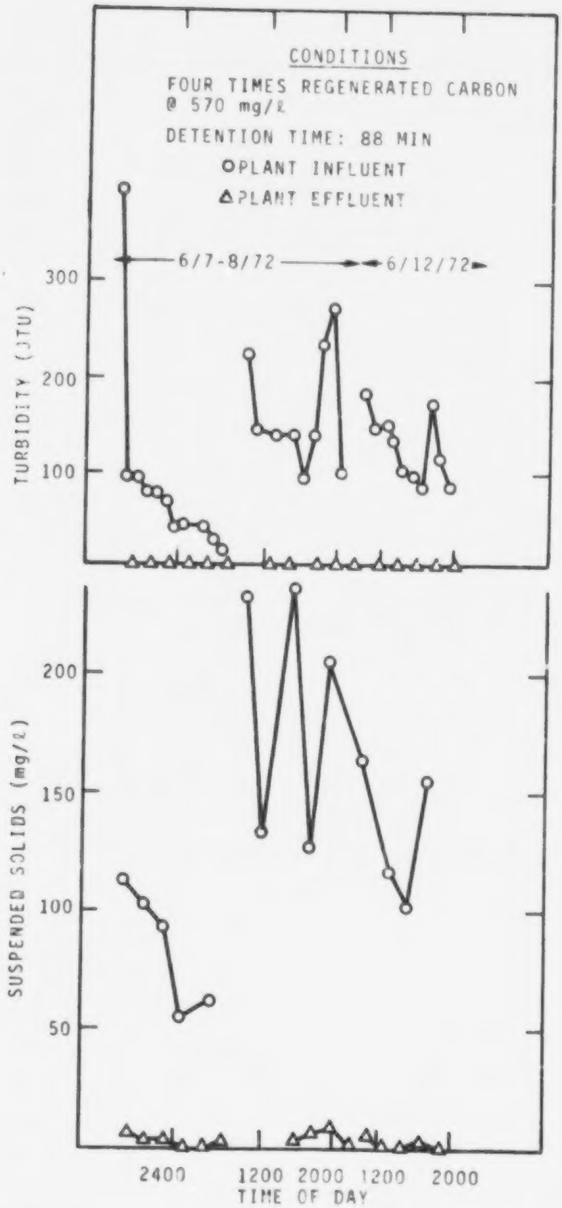


FIGURE 56. PLANT TURBIDITY AND SUSPENDED SOLIDS REMOVAL 6/7-8/72 & 6/12/72

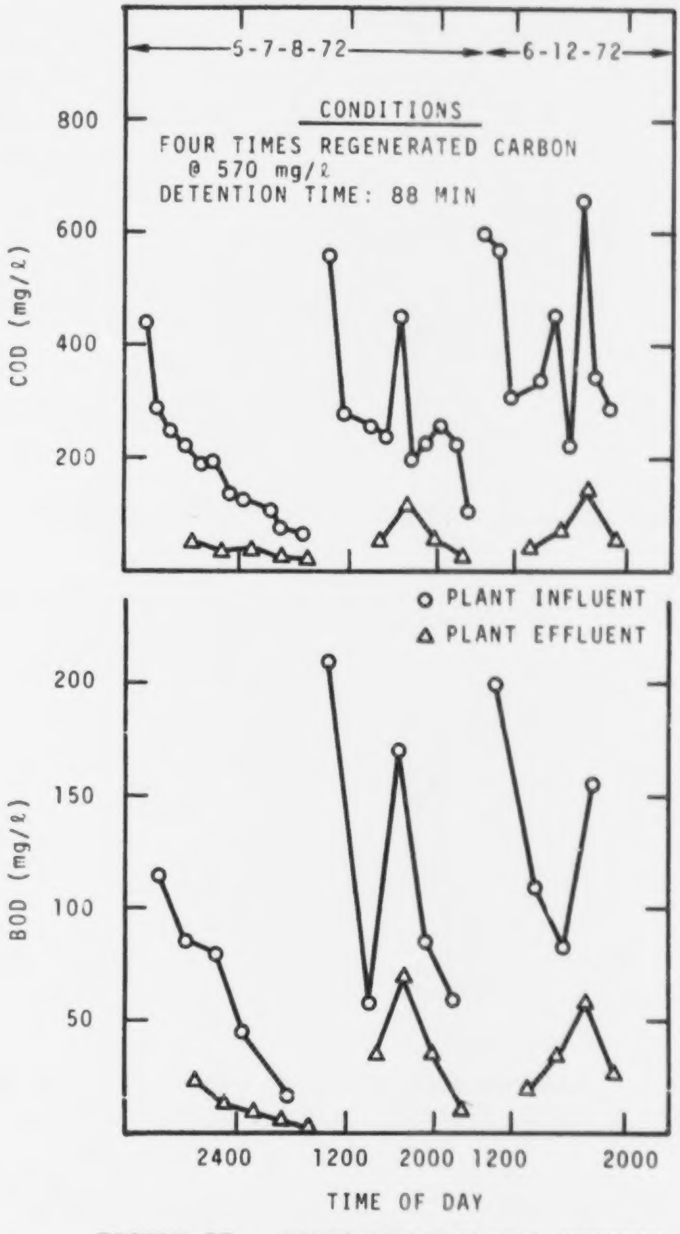


FIGURE 57. PLANT COD AND BOD REMOVAL
6/7-8/72 and 6/12/72

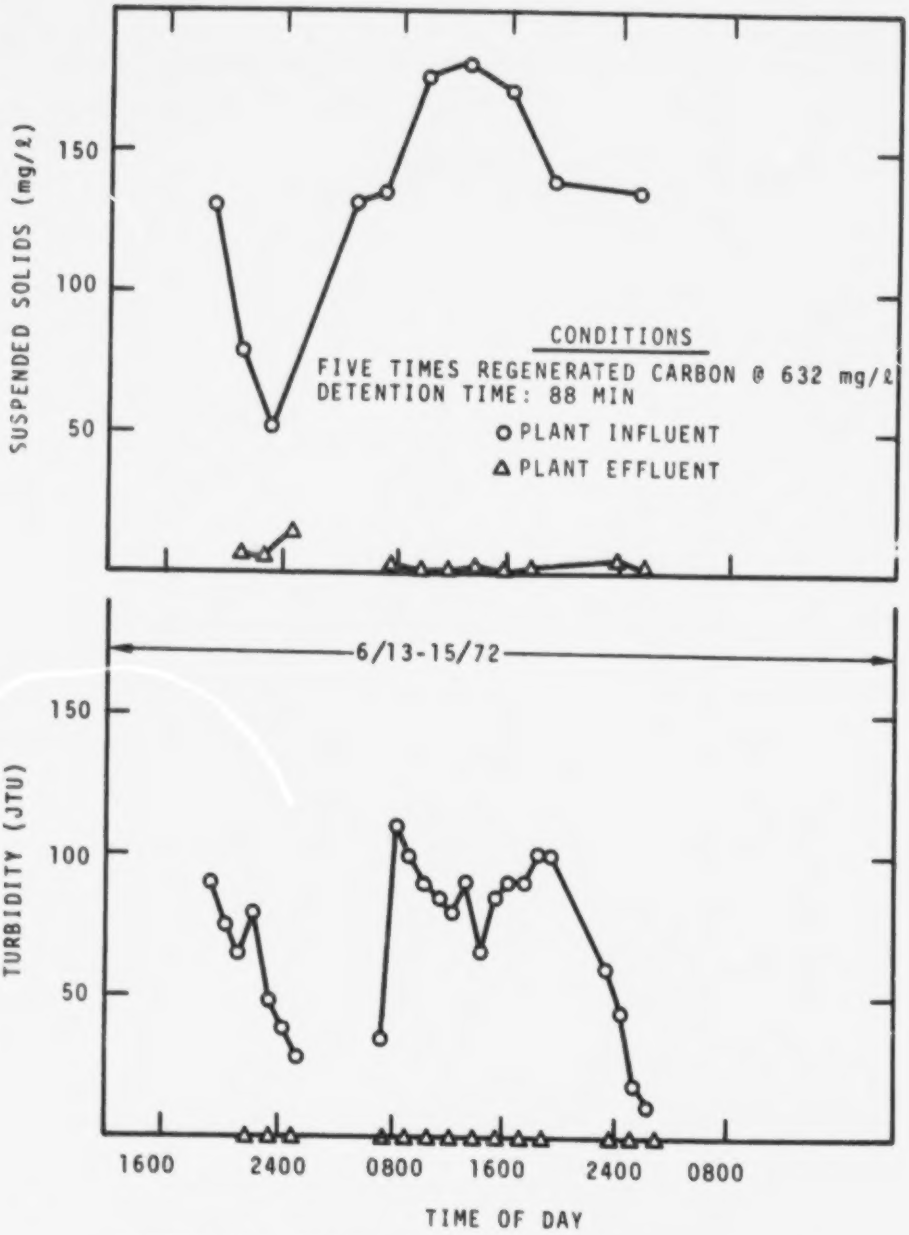


FIGURE 58. PLANT TURBIDITY AND SUSPENDED SOLIDS REMOVAL 6/13-15/72

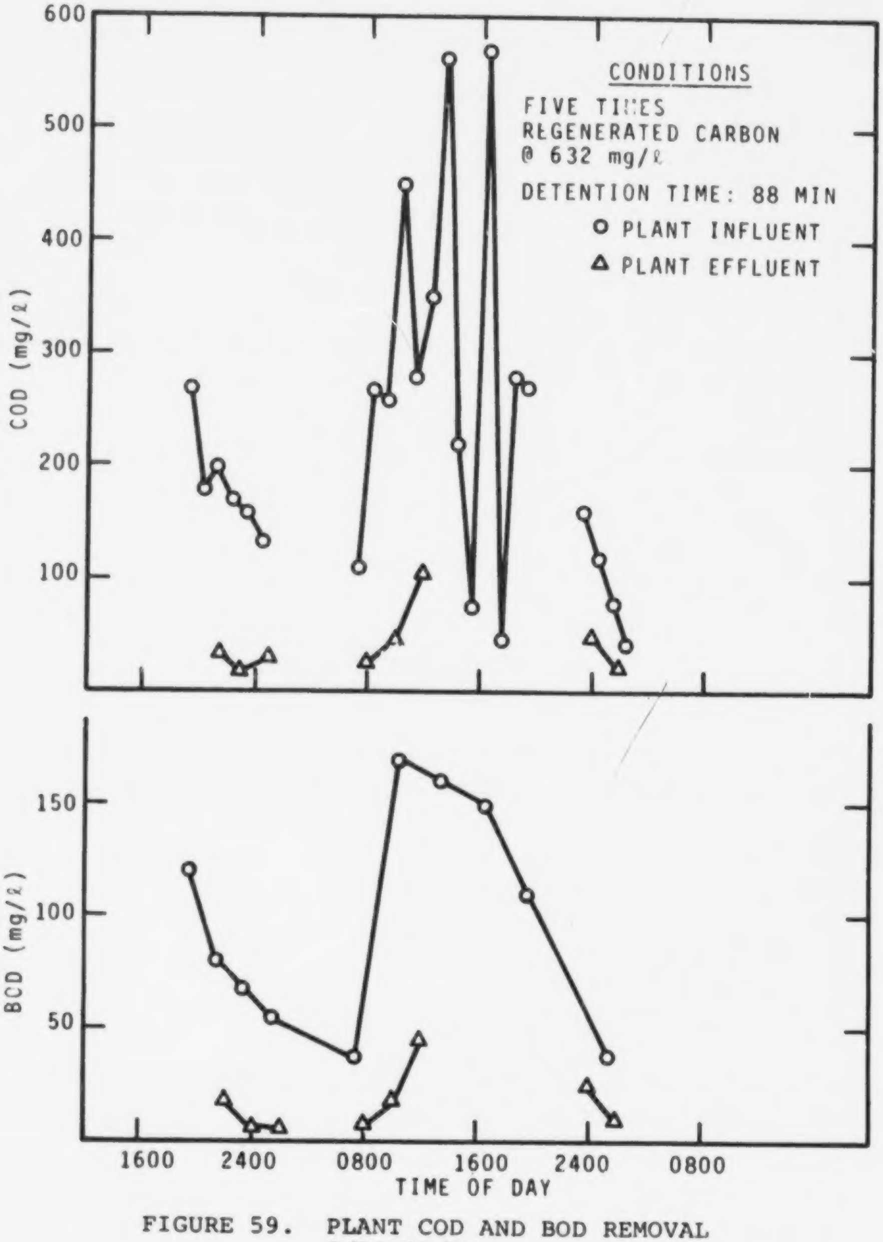


FIGURE 59. PLANT COD AND BOD REMOVAL
6/13-15/72

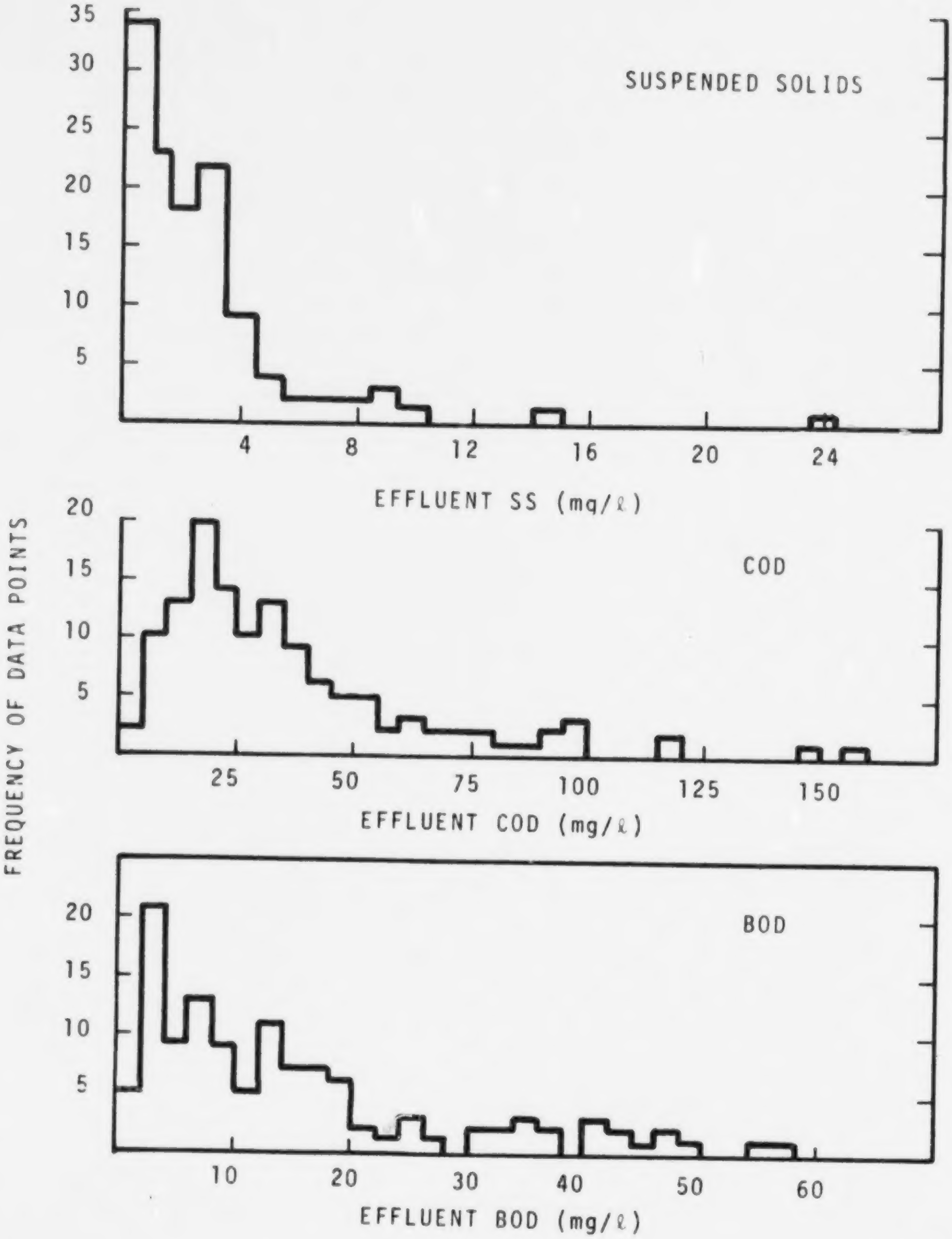


FIGURE 60. FREQUENCY DISTRIBUTION OF PILOT PLANT EFFLUENT QUALITY

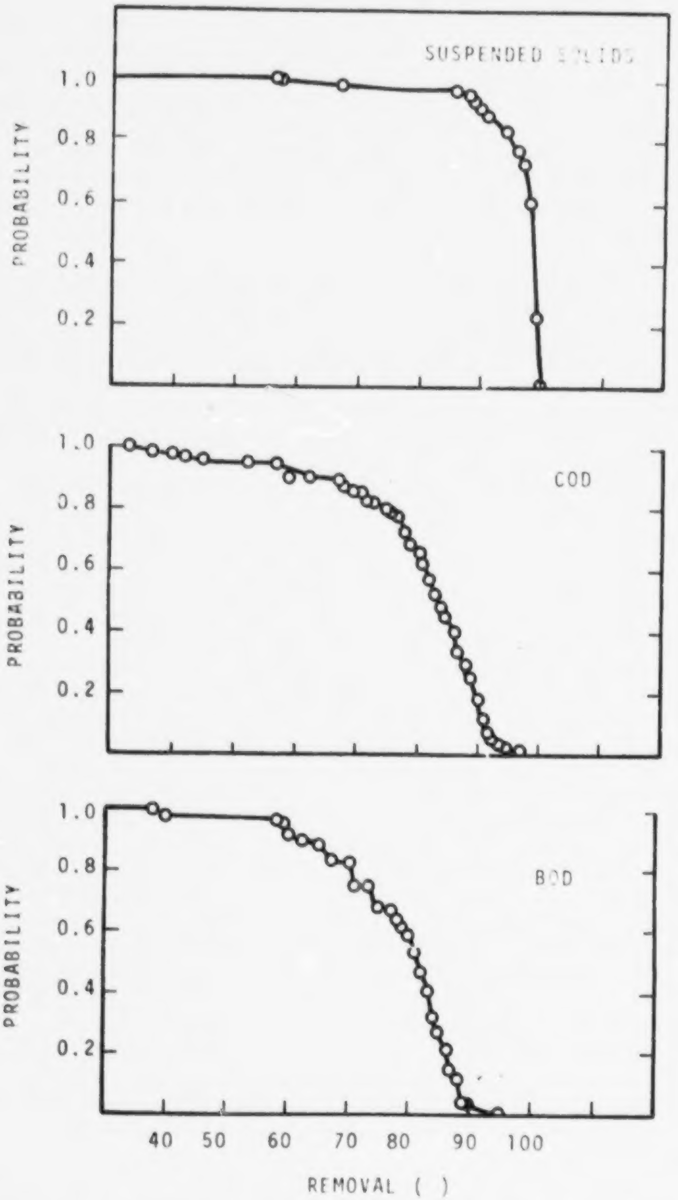


FIGURE 61. CUMULATIVE PROBABILITY DISTRIBUTION OF ACHIEVING REMOVAL PERCENTAGES GREATER THAN OR EQUAL TO A GIVEN VALUE

pilot studies with granular carbon by others(6,7,8), but was observed in a recently completed pilot study in Cleveland, Ohio(9). This suggests that in some cases, physical-chemical treatment of raw municipal wastes may not achieve greater than secondary levels of biodegradable organic removal while in other instances, tertiary levels can be realized. Each waste stream must be examined on a case by case basis to determine the level of BOD removal which can be achieved. Although, for a significant portion of the time, tertiary levels of BOD and COD removal were achieved at the Albany site, on an average basis tertiary levels of BOD and COD removal were not achieved. Tertiary turbidity and suspended solids effluent quality were consistently realized in the pilot operations.

One of the attractive features of the powdered carbon treatment process is the ability to vary the carbon dose with the strength of the influent waste stream. Although any attempt at continuous variation in carbon dose would probably present operational problems which would render this approach impractical, once a waste stream has been characterized, it should be possible to operate at two or three predetermined carbon doses during the course of a day. In fact, this concept was tested during the night hours at the Albany site. After it had been established that the influent waste strength was fairly weak between the hours of 2200 and 0600, the carbon dose was reduced to 0-400 mg/l during this time period for several days with the results given in Table 7. These tests established that the carbon dose could be drastically reduced during the nighttime hours while maintaining a high quality effluent. The data of Table 7 indicate that suspended solids removal is independent of carbon dose as would be expected. Moreover, in the 200 to 400 mg/l range, BOD and COD removal is independent of carbon dose during this portion of the day. Subsequent to these findings, during the months of September and October 1971, the carbon dose was routinely reduced to the 200 mg/l level between the hours of 2200 and 0600 with no detectable decrease in plant effluent quality. Decreasing the carbon dose to a low level during the portion of the day when the wastewater has a low soluble organic content can significantly reduce operating costs without sacrificing treatment efficiency. For example, if a plant were operated at a carbon dose of 600 mg/l for sixteen hours a day and at 200 mg/l for eight hours, the average carbon dose would be substantially below 600 mg/l (the actual dose would depend upon flow variations). Since carbon is the single most important operating cost item in the treatment process, any significant reduction in carbon dose represents a major economy in operating costs.

TABLE 7

PILOT PLANT PERFORMANCE AT LOW CARBON DOSES

	Plant Influent			Plant Effluent		
Time of Day	Suspended Solids (mg/1)	COD (mg/1)	BOD (mg/1)	Suspended Solids (mg/1)	COD (mg/1)	BOD (mg/1)
400 mg Carbon/1 8/19/71						
2400	33	162	58	5	17	9
0200	14	116	37	7	21	10
0400	18	58	21	7	12	6
0600	21	37	29	5	12	3
200 mg Carbon/1 8/25/71						
2400	64	204	58	1	12	8
0200	32	63	24	31	8	3
0400	48	35	12	1	<1	2
0600	37	55	28	2	4	3
0 Carbon 8/27/71						
2400	40	157	76	3	54	19
0200	86	134	45	<2	23	12
0400	18	100	26	4	37	8
0600	54	979	41	4	54	14

Although a high degree of soluble phosphorus removal was achieved in the pilot operations, such a result is not expected in an operating plant. In the pilot plant, excess alum was added at times as discussed in Section VII of this report. However, in actual plant operations, phosphorus removed by the alum in early cycles would be recycled with the regenerated carbon and recovered alum in later cycles.

An equilibrium condition would be established with no net soluble phosphorus removal if there were no blowdown of regenerated carbon. However, since the phosphorus concentration in the regenerated carbon-alum stream is high and blowdown will be required, some phosphorus will be removed from the system. The makeup alum required by a five percent blowdown will provide an anticipated equilibrium soluble phosphorus removal of 31 percent.

The chlorine demand of the pilot plant effluent was investigated. Two samples drawn at different times of the day (1400 and 2200) were treated with various chlorine doses and allowed contact times of 15 and 30 minutes as shown in Figure 62. The chlorine residual after 30 minutes contact averaged 0.2 mg/l less than with 15 minutes contact.

Coliform analyses were run at various times of the day. The results in colonies/100 ml sample are presented below.

Time Sample Taken:	0600	0900	1600
Raw Sewage	1,150,000	4,700,000	15,900,000
Tube Settler Effluent	872	18,000	7,500
Filter Effluent	584	14,100	7,000

Removal of coliforms in the plant was found to average 99.9 percent without disinfecting the effluent. It was observed that filtering the tube settler effluent removed an additional ten percent of the clarifier effluent coliforms.

Filtration of the tube settler effluent at the Albany site was also observed to significantly improve pollutant removal performance. The filtered effluent averaged 7 percent lower in suspended solids and 20 percent lower in COD and BOD than the tube settler effluent. This may have been due in large part to the previously discussed operational problems associated with the pilot tube settler.

The average neutralization lime usage was 190 mg/l. As seen from Figure 63, the dose varied substantially from run to run

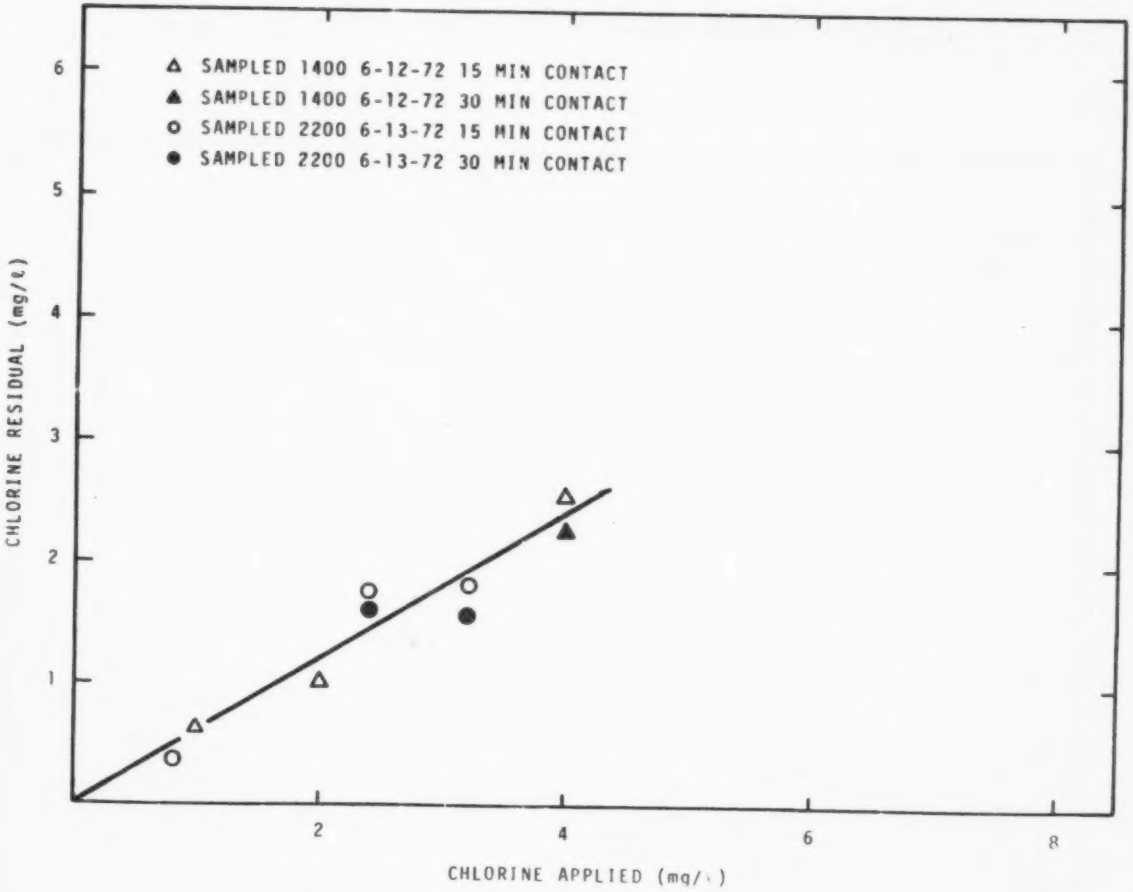
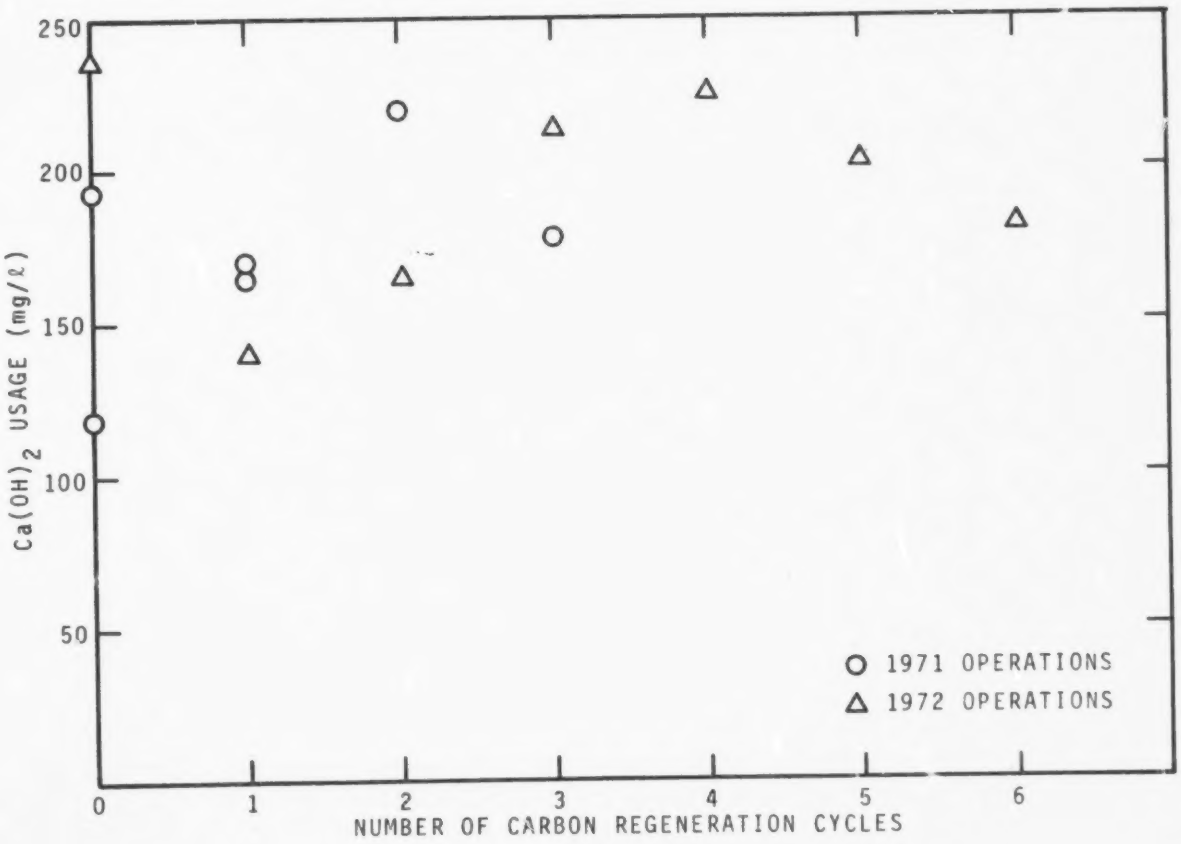


FIGURE 62. CHLORINE DEMAND OF PLANT EFFLUENT



such that no significant trend is observed. It is anticipated that a reduction in lime dose below this level can be achieved since, as discussed in Section VII of this report, it is believed that the acid requirement for alum recovery can be substantially reduced below that employed in the pilot studies.

Discounting equipment failures in the pilot system, the treatment process proved to be highly reliable and was capable of consistently producing a high quality effluent.

REGENERATED CARBON PERFORMANCE

Regenerated carbon and reclaimed alum performed as well as the virgin substances in the pilot system. In all of the runs with the recovered products, coagulation and sedimentation proceeded normally. The removal of organic matter from the raw wastewater was good during the runs with regenerated carbon. Data on the system performance with virgin carbon and with regenerated carbon are presented in Table 8 and Figures 40-47 and 50-59. It is evident from the data of Table 8 that even with regenerated carbon at fixed carbon doses as low as 370 mg/l, the pilot plant COD, BOD, and SS removals are comparable to a virgin carbon dose of 600 mg/l. After seven regeneration cycles, the sorption performance of the carbon was essentially that of virgin carbon as evidenced by the pilot plant data and the jar test data presented in Figures 66-74 (Section VII).

TABLE 8

Regenerated Carbon Performance Comparison

	Carbon Batch	Fixed Carbon Dose (mg/l)	Plant Influent				Plant Effluent				Plant Removal			
			COD (mg/l)	BOD (mg/l)	SS (mg/l)	Turbidity (JTU)	COD (mg/l)	BOD (mg/l)	SS (mg/l)	Turbidity (mg/l)	COD %	BOD %	SS %	Turbidity %
Virgin*		600	276	104	130	--	35	17.8	7.7	--	87	83	94	--
1.0 Regenerations	A	650	278	--	--	--	27	14	3.7	--	90	--	--	--
1.9	A	580	411	--	135	--	56	23	7.0	--	86	--	95	--
2.8	A	370	690	--	248	--	45	36	18.2	--	94	--	93	--
3.7	A	470	337	160	85	--	44	14	3.1	--	87	91	96	--
0.9	B	540	246	142	--	--	43	27	--	--	82	81	--	--
Virgin	C	601	187	69	139	101	29	12	2.5	0.55	85	82	98	>99
1.0	C	633	323	133	190	90	47	24	2.5	0.84	85	82	99	>99
1.9	C	570	286	106	206	102	46	18	4.4	0.99	84	83	98	99
2.9	C	506	192	80	214	294	41	17	4.2	0.66	78	79	98	>99
3.8	C	570	291	106	139	119	56	26	3.1	0.47	81	75	98	>99
4.8	C	632	224	99	133	70	31	13	3.9	--	86	87	97	--

*Data from two months operation, daily composite samples

SECTION VII

REGENERATION

OPERATIONAL PROCEDURES

During that portion of the 1971 pilot studies that the carbon regeneration facility was operational, the liquid treatment system and carbon regeneration system were operated alternately on a campaign basis. The treatment system was operated for a twenty-four hour period or until approximately 500 pounds of activated carbon was consumed. Sludge was stored until the treatment operation was completed and then was dewatered in the centrifuge and fed into the fluidized bed furnace.

In the 1972 portion of the program, the liquid treatment system and the carbon regeneration system were operated simultaneously. For any given cycle, the treatment portion of the pilot plant was operated alone until sufficient carbon had been accumulated for the regeneration operation to commence. Both systems were then operated until approximately 1000 pounds of carbon was exhausted in the treatment process. The treatment system was then shut down until the next cycle was begun.

Regenerated carbon-aluminum oxide slurry from the off gas scrubber was collected in holding tanks during furnace operation. Supernatant water from these storage tanks was continuously decanted and recycled through the venturi scrubber until the slurry concentration in the tanks built up to approximately six percent carbon, which was suitable for use in the treatment operations. Cooling of the recycled slurry from the venturi scrubber was not necessary since it left the disengaging vessel at 60°C. When the slurry concentration in the carbon tanks had reached the desired concentration, a pH adjustment to pH 2 was then effected with sulfuric acid and the necessary makeup carbon and alum were added to the storage tanks.

Samples of virgin and regenerated carbon slurries were analyzed for fixed carbon content. Analyses were obtained by combusting a sample at 1200°C in a pure oxygen atmosphere and then chromatographically determining the carbon dioxide produced. Reproducibility using this technique was consistently within five percent. Attempts were made to analyze the fixed carbon content of spent carbon sludge by heating at selected temperatures to drive off organics prior to combusting a sample. However, no reproducible results could be obtained. Since the fixed carbon content of the sludge feed to the regeneration furnace could not be determined, it was necessary to determine carbon losses on the basis of a mass balance across the entire system. Virgin and regenerated carbons did not contain the organic component which created analytical errors in carbon analysis of carbon sludge samples.

Alum recovery was also determined on a mass balance basis. Samples were drawn from each of the acidified carbon slurry tanks, filtered through 0.45 micron membrane filter and the filtrate was then analyzed for aluminum as outlined in Standard Methods(10).

Due to the fact that the regeneration furnace became operational so late in the 1971 portion of the program, there was only a limited time available for regeneration studies. Thus it was deemed necessary to complete each regeneration-reuse cycle in the minimum time possible in order to achieve a maximum number of cycles. Therefore, there was insufficient time to obtain analytical results on carbon recovery following a regeneration cycle prior to commencing the next treatment cycle of the operation. As a result, 1971 carbon doses in the treatment system were lower at times than desired.

Makeup activated carbon was not added in the first two 1971 regeneration cycles but was added routinely after the second cycle in order to maintain a total quantity of 500 pounds of fixed carbon. Sufficient alum was added after each regeneration to maintain the aluminum concentration in the feed solution at 1.6 g/l.

In the 1972 operation, the carbon inventory was initially maintained at 1000 pounds of fixed carbon. Following the fourth regeneration cycle, the inventory was reduced to 500 lbs to decrease the time required per regeneration cycle. Virgin carbon and alum were added as necessary to compensate for losses.

At times it became necessary to begin using a tankful of regenerated carbon before the results of the aluminum analysis became available. To be certain of a minimum feed strength of 1.6 g/l aluminum, alum was added beyond what was actually required. Thus the actual alum concentration in the treatment system was sometimes higher than 200 mg/l.

SYSTEM STARTUP

Numerous mechanical problems with the furnace equipment were encountered during the startup phase of the operation. Most of these problems were minor in nature and were easily corrected. However, several major difficulties of a more persistent nature caused a significant delay in actual furnace operations. These major problems involved heat leakage around the hearth, lower door, and burner. A great deal of time and effort was expended in resolution of these problems. Final sealing of these leaks involved replacement of the burner assembly and redesign and replacement of the hearth and lower door. Although the initial construction of the furnace was complete on May 27, 1971, the regeneration system did not become fully operational until September 17, 1971.

During the 1971 operation, the extra strength castable hearth developed deep cracks necessitating replacement twice during the campaign. This was corrected prior to commencement of the 1972 operation by replacing the castable hearth with a brick hearth and by modifying the controls such that the combustion air system was automatically shut down in the event of a flame failure. Previously, following flame failure, the combustion air at 150°F continued to blow into the 1900°F firebox, thus not allowing the fluidized bed sand to percolate through the hearth. It is believed that the thermal shock thus produced played a major role in previous hearth failures. Following these modifications, no major startup problems were encountered in the spring of 1972.

FURNACE OPERATIONS

Due to the fact that the fluidized bed furnace became operational so late in the 1971 portion of the pilot program, there was little latitude for experimentation with the operating conditions. Using a ten inch diameter furnace, it had previously been established that good carbon regeneration and recovery could be obtained at a bed temperature of 1250°F and an oxygen level of less than one percent in the stack gas(11,12). Therefore, these conditions were followed in the pilot runs at Albany. Operating conditions for the fluidized bed furnace are given in Table 9. Bed velocities reported in Table 9 are calculated at a point midway up the bed using the superficial area at that point. The gas velocity in the freeboard zone is 0.785 times the reported bed velocity.

A total of six carbon regenerations were accomplished in the pilot operations in 1971. Runs 1-4 represent a single batch (Batch A) of powdered carbon followed through consecutive cycles of use and regeneration. At the end of the fourth regeneration, a substantial quantity of the carbon was lost due to an operational problem; therefore, it was necessary to begin again with virgin carbon at this point. Runs 5 and 6 represent the first and second regenerations of the second batch (Batch B) of carbon. Runs 7-13 represent a single batch (Batch C) of carbon regenerated seven times.

TABLE 9

FLUIDIZED BED-FURNACE OPERATING CONDITIONS

Regeneration No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Carbon Batch	A	A	A	A	B	B	C	C	C	C	C	C	C
Bed Temperature (°F)	1290	1260	1250	1250	1250	1260	1280	1270	1260	1250	1260	1240	1220
Firebox Temperature (°F)	1900	1880	1910	2030	1980	1905	1840	1900	1860	1860	1860	1860	1880
Bed Velocity (ft/sec)	1.4	1.6	1.6	1.4	1.3	1.1	1.7	1.5	1.7	1.9	2.1	2.2	2.2
Recycle Gas Flow (SCFM)	83	89	83	60	60	63	61	62	78	107	123	126	138
Combustion Air Flow (SCFM)	71	89	86	82	68	63	80	68	66	64	59	67	60
Propane Flow (SCFM)	3.0	3.7	3.6	3.4	2.8	2.6	3.5	3.0	2.9	3.1	3.3	3.7	3.6
Sludge Feed Rate (lbs/hr)	120	125	120	120	115	80	119	105	96	64	94	106	117
Solids Concentration in Feed (%)	21.7	24.1	22.9	22.6	23.5	22.9	22.0	21.1	21.9	21.9	23.5	25.7	-

Since it was impractical to completely drain all of the carbon from the treatment system prior to each regeneration cycle, a fraction of the carbon was not regenerated each cycle. In the case of the 1971 runs, this represented 4-10 percent of the carbon per cycle. The result was that even though four cycles were completed in the case of the first batch of carbon, the actual number of regenerations was only 3.7.

Due to the larger carbon inventory of the 1972 runs, the system holdup represented a smaller fraction of the total carbon. Runs 7-13, a total of seven cycles, provided 6.7 actual carbon regenerations.

The temperature of the fluidized sand bed was monitored by four thermocouples evenly spaced around the bed at various levels. It was observed that temperatures at all four points could be maintained within a 50°F range when the bed was properly fluidized. At low gas flow rates through the bed, the thermocouple opposite the carbon feed point indicated temperatures higher than the thermocouple adjacent to the entering slurry, a result of poor bed fluidization. Temperatures in the freeboard zone measured near the furnace gas outlet consistently registered 50-100°F lower than the bed temperature.

The firebox temperature was maintained below 2100°F to avoid damage to the furnace material. Temperature was regulated by controlling the ratio of combustion air to recycle gas. Recycle gas entering at 150-200°F cooled the firebox while keeping the oxygen level low and providing the proper fluidization gas flow.

An effort was made to maintain the bed velocity at as low a level as possible in order to minimize attrition of the sand and also to prevent sand carryover with the carbon. However, it was observed that at fluidizing velocities of about 1 ft/sec or less, heat transfer from firebox to bed was much poorer than at higher velocities. During Run 3, at a velocity of 1.6 ft/sec, 120 lbs/hr of sludge could be fed while keeping the bed at 1250°F and the firebox about 1900°F. However, when the fluidizing velocity was decreased, it was necessary to substantially decrease the sludge feed rate to the furnace in order to maintain the desired temperature. For example, in Run 6, when the fluidizing velocity was decreased to 1.1 ft/sec, the sludge feed rate had to be correspondingly reduced to 80 lbs/hr in order to maintain a bed temperature of 1260°F.

It was necessary to maintain the combustion air blower in continuous operation even when the regeneration furnace was not in use in order to prevent the sand from flowing through the holes in the hearth and into the firebox. This contributed to attrition of the sand in the furnace which was observed to be substantial. Sieve analyses of the sand both before use and after 21, 35, and 41 days of fluidization in the furnace are presented in Table 10. If attrition cannot be substantially reduced, periodic withdrawal and replacement of the sand appears indicated. It is suggested that provisions for keeping the sand above the hearth during blower shutdown be included in the design of the hearth. Proper installation of bubble caps may provide good horizontal distribution of the gas while checking sand flow into the firebox during blower shutdown.

The oxygen content of the fluidized bed off gas was determined by Orsat Analysis. Once the proper O_2 level was attained, a Hayes Model 635 oxygen analyzer continuously monitored the level. Periodic adjustments of the fuel-air ratio were made as necessary to maintain the oxygen content of the stack gas at the 0-0.5 percent level.

One of the major operational problems which occurred during the course of the program was plugging of the holes in the hearth. Toward the end of the 1971 operations in Albany, the pressure drop across the hearth rather suddenly increased to the point where shutdown was necessary. Inspection of the system revealed that sand was caking inside the holes in the hearth, thus restricting the gas flow.

Prior to beginning the 1972 operation, a 6 inch layer of 3/4 inch diameter high temperature gravel was placed on top of the hearth. It was felt that this would provide an additional buffer layer between the 1250°F bed and the 2000°F firebox as well as reduce the amount of sand that percolates through the hearth during furnace shutdowns. About two weeks after regeneration began during the 1972 campaign, the hearth pressure drop again became excessive. Inspection of the hearth revealed that the 6 inch layer of gravel on the hearth had become cemented together into one large mass. X-ray analysis showed the "cement" to contain a large amount of magnetite. (The presence of a mixture of FeO and Fe_2O_3 is understandable since maintaining an oxygen level in the fluidized bed slightly above zero required frequent adjustments in operating conditions. Although the furnace atmosphere was normally slightly oxidizing, at times, reducing conditions probably existed.) The caked sand removed from the inside of the hearth holes also was found to contain large amounts of magnetite. Plugging of the holes in the hearth continued to be a problem throughout the 1972 portion of the program.

In addition to causing periodic system shutdown, plugging presents other potential problems. It is believed that as some of the holes plugged with sand and magnetite, nonuniform fluidization occurred. In this case, spouting of the bed

TABLE 10

SIEVE ANALYSES OF FLUIDIZED BED SAND

Sand Retained on Screen #	Quantity Retained (g)	Fraction Quantity Retained (%)
Virgin Ottawa Flint Shot Sand		
20	8.6	1.67
30	325.0	63.04
40	164.0	31.81
50	16.0	3.10
Pan	1.9	0.37
	515.5	99.99
Furnace Sand Collected After 21 Days Fluidization		
20	0.89	0.38
30	99.18	41.97
40	116.46	49.28
50	12.79	5.41
60	3.66	1.55
70	0.88	0.37
100	1.59	0.67
Pan	0.86	0.36
	236.31	99.99
Furnace Sand Collected After 35 Days Fluidization		
20	0.88	0.21
30	121.68	28.78
40	139.83	33.07
50	63.31	14.97
60	45.14	10.68
70	24.67	5.83
100	26.33	6.23
Pan	0.97	0.23
	422.81	100.00
Furnace Sand Collected After 41 Days Fluidization		
20	2.4[1]	0.56
30	112.8	26.58
40	140.4	33.09
50	77.4	18.24
60	42.0	9.90
70	23.3	5.49
100	20.8	4.90
Pan	5.2	1.23
	424.3	99.99

---

[1] Contained about 1 g of chunks of fused material from the furnace.

material could occur causing increased sand carryover into the product. Uneven fluidization would also result in nonuniform carbon retention times thus reducing the carbon regeneration efficiency.

Identification of the source of iron became of major importance since iron appeared to be the cause of the biggest operational problem in the regeneration system. An iron inventory for each regeneration cycle was determined with the results as shown in Figure 64.

It was noted that the actual iron inventory increased initially and then leveled off at about 13 pounds. However, when physical losses were taken into account, the iron inventory increased more or less constantly for the first five cycles at about six pounds per cycle. An identification of the possible sources could not account for anywhere near this quantity of iron. The maximum possible contributions of iron from various sources were identified as follows

Fe from sewage treated	0.39 lbs per cycle
Fe from lime impurities	0.35
Fe from alum impurities	0.64
Fe from H_2SO_4 impurities	0.01
Total Fe	1.39 lbs per cycle

Thus a maximum of 1.4 pounds of iron per cycle could be identified as possibly entering the system from known sources. This left 4.6 pounds of iron per cycle which could not be attributed readily to any source.

When the holes in the hearth plugged, the caked material filled the entire six inch length of the holes. This suggested that the iron was entering the system below the hearth since it appeared unlikely that material could work down from the top of the hearth and plug the holes in depth while the high velocity gas stream was blowing upward through the holes. In addition, the absence of any significant quantity of aluminum in the materials which caked in the hearth holes indicated that a special source of iron introduced below the hearth was responsible for the plugging. Neither the fresh air stream nor the propane stream were probable sources of large quantities of iron. Therefore, it was deduced that the iron was probably entering the firebox in the recycle gas stream.

Shortly after the iron buildup was discovered, the recycle gas blower failed. It was discovered that two of the thirteen blower fans were severely corroded and consequently were out of balance thus causing the blower failure. Further inspection of the remainder of the recycle gas system revealed

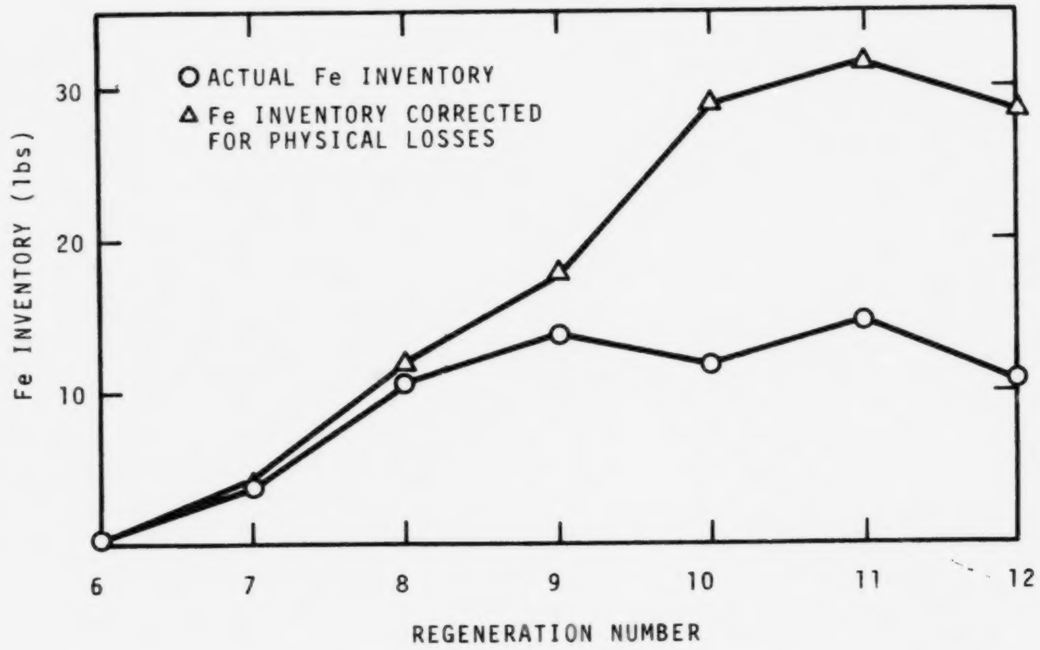


FIGURE 64. IRON INVENTORY IN REGENERATED CARBON SLURRY

that the inside of the six inch diameter black iron piping was covered with a rust scale that was easily dislodged. Following repair of the blower, the recycle gas stream was closely observed and it was noted that large clouds of red dust (presumably rust) were often present in the recycle system at blower startup. Thus, it was concluded that the major source of iron which caused plugging of the hearth derived from corrosion of the recycle gas system.

Design of a corrosion resistant recycle gas system should eliminate the introduction of iron into the firebox and thus should eliminate the hearth plugging problem. This would reduce the total iron buildup to a maximum of 1.4 pounds per cycle or 0.0018 pounds of iron per pound of carbon used. However, this residual iron should not cause plugging problems in the hearth since it would be introduced into the fluidized bed zone of the furnace and thus should not work down to plug the hearth. Installation of bubble caps should provide additional insurance against the hearth plugging from the top down. Therefore, it is concluded that the serious plugging problems encountered in the Albany pilot plant operations can be easily precluded by proper use of corrosion resistant materials of construction.

The buildup of inert material in the carbon following each regeneration is plotted in Figure 65. Batch A regenerations are characterized by a high initial increase in inert material in the first regeneration cycle and then a gradual increase in inert content at the average rate of 3.2 percent per cycle for successive regenerations. In the case of carbon Batch B, insufficient data are available to establish a trend. Inert material buildup in the third batch of carbon (Batch C) followed the same general trend as that established for the first carbon batch -- a high initial buildup of inert material in the first regeneration cycle and then a gradual increase in subsequent cycles, in this instance at the rate of 2.8 percent per cycle. During the seventh regeneration cycle, the sand trap on the product line failed for a portion of the run thus permitting a higher than usual sand carryover into the product and consequently, a higher inert buildup.

Average inert material buildup in the carbon for cycles subsequent to the first cycle was 2.9 percent per cycle for the entire pilot plant operation. The average fixed suspended matter of 23 daily composite sewage samples was 41 mg/l. Considering that 94 percent of the suspended solids are removed in treatment at a carbon dose of 600 mg/l, the regenerated carbon should build up ash at the rate of 6.4 percent per cycle. Actual pilot plant data show a 2.9 percent buildup. It is likely that acidification of the regenerated carbon to pH 2 dissolves a significant quantity of the ash.

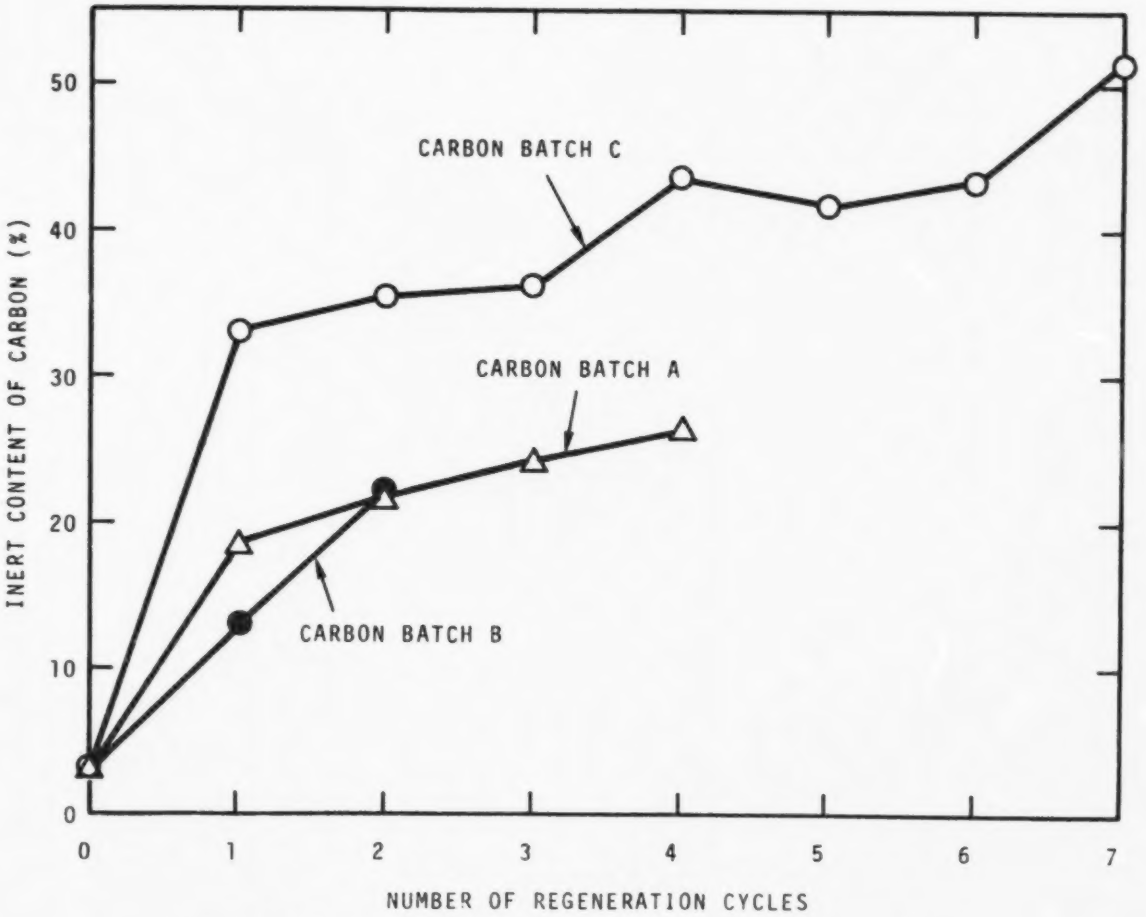


FIGURE 65. INERTS BUILDUP IN REGENERATED CARBON

Most of this dissolved ash is probably discharged in the product water from the liquid waste treatment system.

Microprobe analyses of the inert material for cations of molecular weight greater than Na revealed Si to be the overwhelmingly predominant species. This result was confirmed by X-ray analyses which indicated SiO_2 was the main constituent of the inert material. These observations suggest that the major component of the inert material in the product from the regeneration furnace was sand.

Since the inert material in the regeneration carbon stream built up at a regular rate for all but the first cycle, it is apparent that special circumstances unique to the first cycle in the cases of carbon Batches A and C must have been responsible for the high initial jump in inerts. Considering carbon Batch A, the 15.5 percent increase in inerts in the first regeneration cycle represents 122 pounds of material. In the case of carbon Batch C, 308 pounds of inert material were required to cause the 30 percent jump in the first cycle.

It appears that a major portion of the inert buildup during the first regeneration of carbon Batch C resulted as a consequence of improper positioning of the plant influent hose in the sewer. Plant influent was drawn from a flat bottom area of the sewer 7.5 feet wide used as a metering chamber. The rear edge of a 12 inch wide by 12 inch deep trench extending across the chamber formed a weir with the depth of overflow being used to determine flowrate. The pilot plant influent line was wedged into this trench to prevent its becoming dislodged during high flows in the sewer. The trench, however, contained a large quantity of sediment and gravel which was drawn into the pilot plant during the first few hours of operation. In fact, the vertical influent hose soon became plugged with gravel.

During the 1971 operations the liquid treatment portion of the plant was operated for several months before the regeneration facility became operational, allowing ample time to clear the sand and gravel from the trough. On the other hand, during the 1972 operation, sludge was collected and regenerated from the start of the treatment operations. Thus, the material sucked from the trough was fed to the furnace with the sludge where it could be abraded and/or thermally cracked in the fluidized bed and then find its way into the product carbon stream.

It is believed that the major portion of the 308 pounds of inert material buildup in the first regeneration of carbon Batch C resulted from this cause. Since a full scale plant would have a grit chamber, a problem of this nature should not occur. In fact, a grit chamber should effect some reduction in inert material buildup in each regeneration cycle and therefore, one would expect a lower average buildup than observed in the pilot runs.

No sufficient reason for the high initial buildup of inert material in the first regeneration cycle of carbon Batch A is evident. The cause cannot be attributed to a high initial attrition of virgin sand and carryover in the product since the furnace sand was completely replaced several times during the pilot program and no high increase in inerts was evident in subsequent regenerations. Thus it appears that the source of the inert material buildup in the first cycle regenerations of both carbon Batches A and C was external to the regeneration system and most probably consisted of material present in the influent waste stream. A grit chamber should eliminate this contribution of inerts to the regenerated carbon.

Following each regeneration cycle, jar tests were run with samples of the regenerated carbon, duplicating as nearly as possible the pilot plant operating conditions. Data from these jar tests are presented in Figures 66-74. Examination of this data indicates that the regenerated and virgin carbons were virtually identical in sorptive capacity. During the first part of the first regeneration run (Batch A), highly unstable temperature and sludge feed conditions persisted in the regeneration furnace. Figure 66 illustrates the adverse effect that these unstable conditions had on recovery of the sorptive capacity of the carbon. Later in the run when the system had stabilized, regeneration was much better as indicated by the sorption curve in Figure 66. The pilot plant data for the regenerated carbon given in Table 8 substantiate the observation that full capacity recovery could be achieved after numerous regenerations.

ALUM RECOVERY

It is well known that aluminum hydroxide goes through the conversion

$$Al(OH)_3 \xrightarrow{500°C} \gamma\text{-}Al_2O_3 \xrightarrow{1000°C} \alpha\text{-}Al_2O_3$$

The γ-oxide readily dissolves in sulfuric acid to yield aluminum ions while the α-oxide is highly acid resistant. Since carbon regeneration is effected in the fluidized bed furnace below 1000°C, the majority of the hydrous aluminum oxide present in the carbon sludge should be converted to the soluble alumina, γ-Al_2O_3, in the regeneration process. The laboratory studies described in Appendix A indicated that it should be possible to recover 80-100 percent of the aluminum following regeneration.

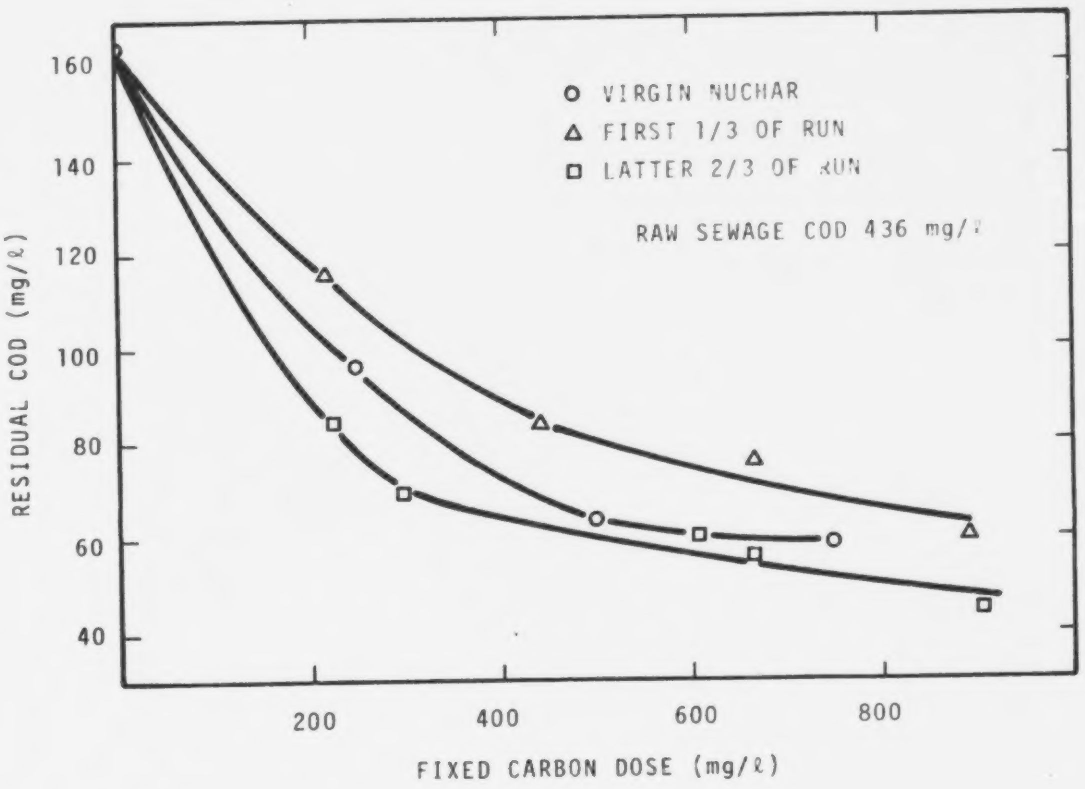


FIGURE 66. JAR TESTS ON ONCE REGENERATED CARBON - BATCH A

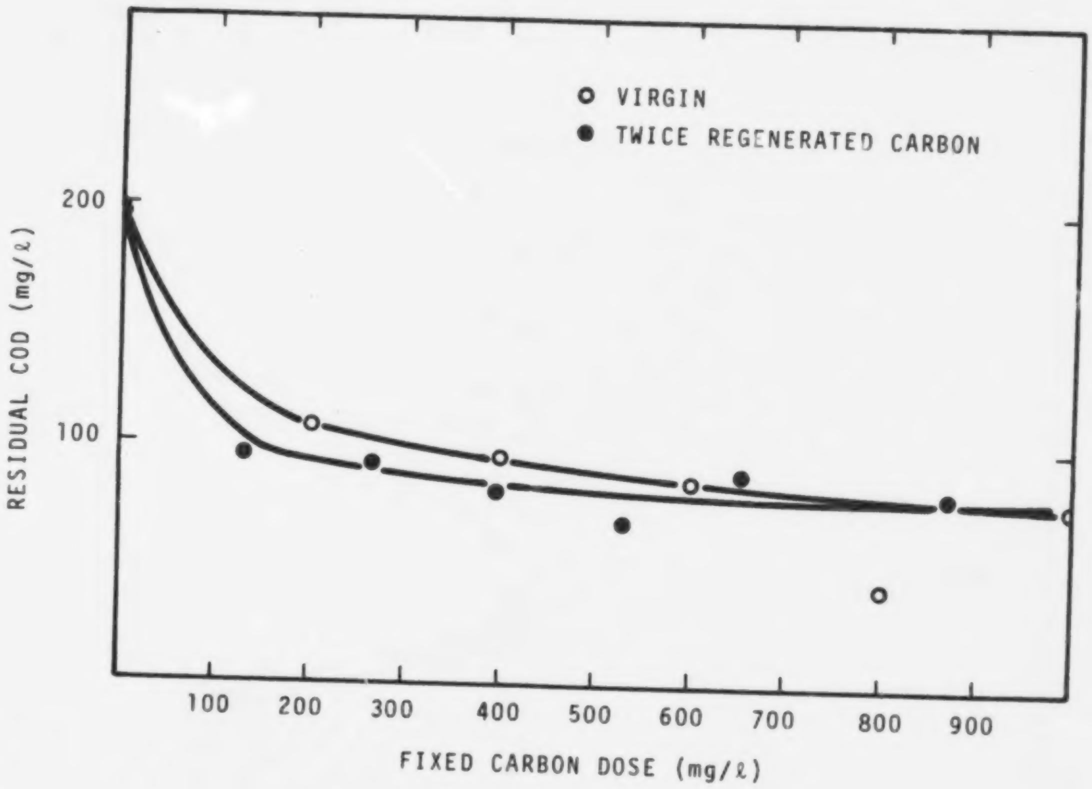


FIGURE 67. JAR TESTS ON TWICE REGENERATED CARBON - BATCH A

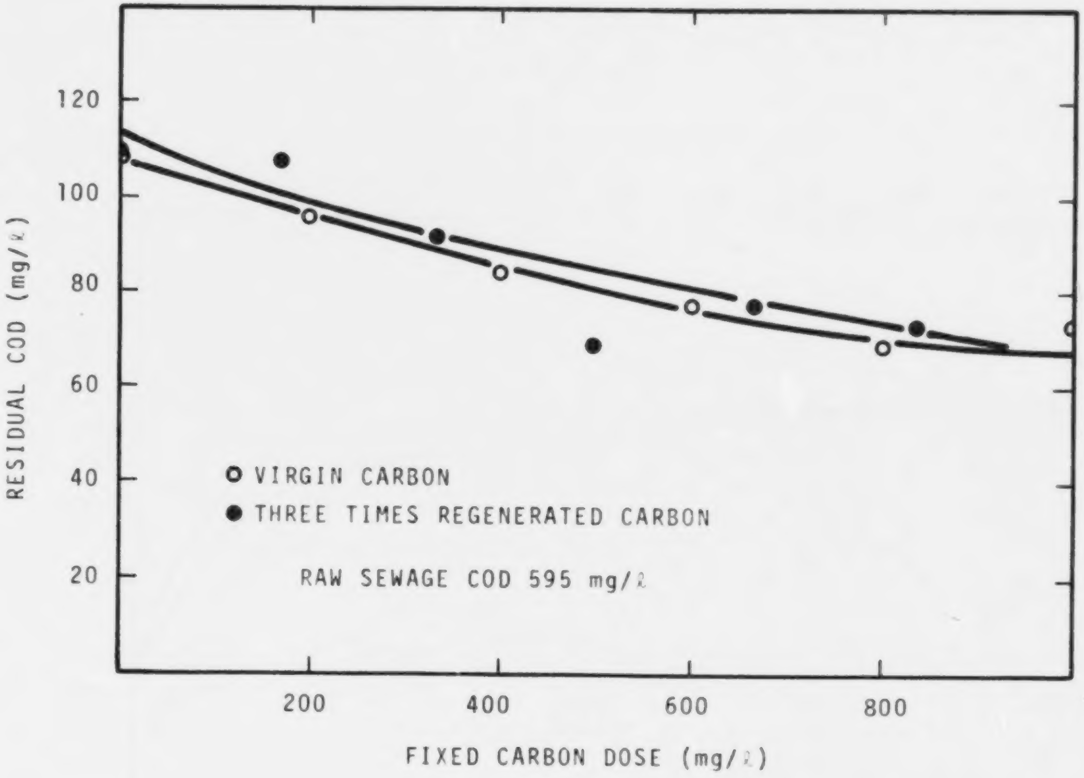


FIGURE 68. JAR TESTS ON THREE TIMES REGENERATED CARBON - BATCH A

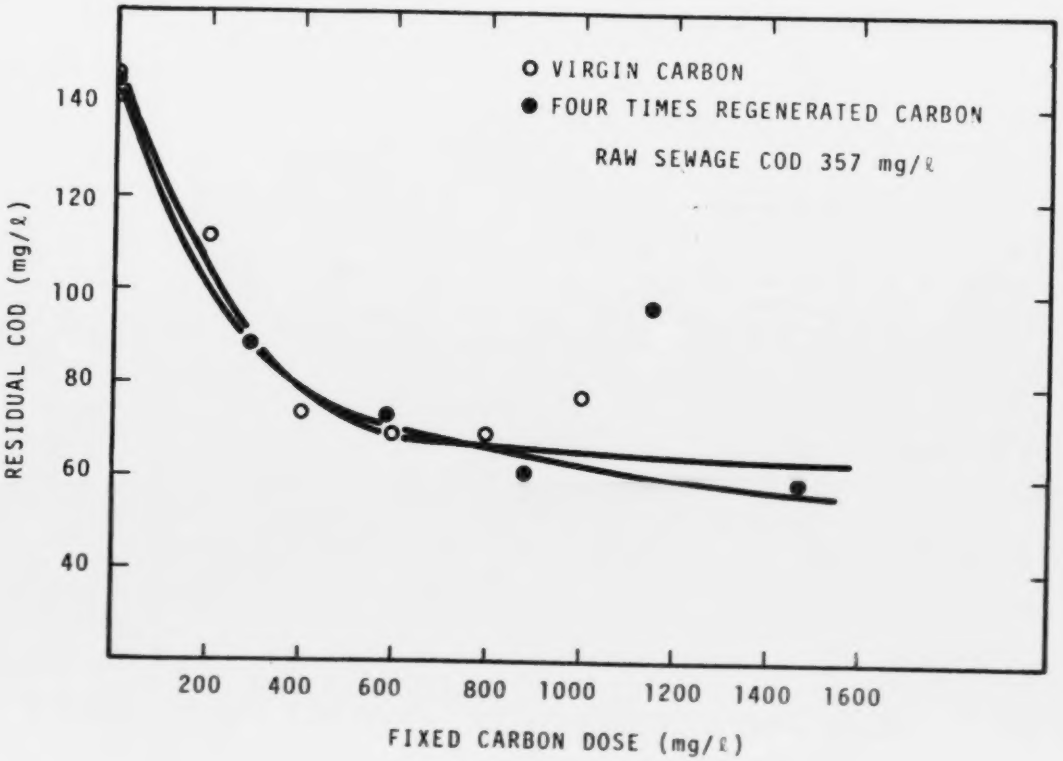


FIGURE 69. JAR TESTS ON FOUR TIMES REGENERATED CARBON - BATCH A

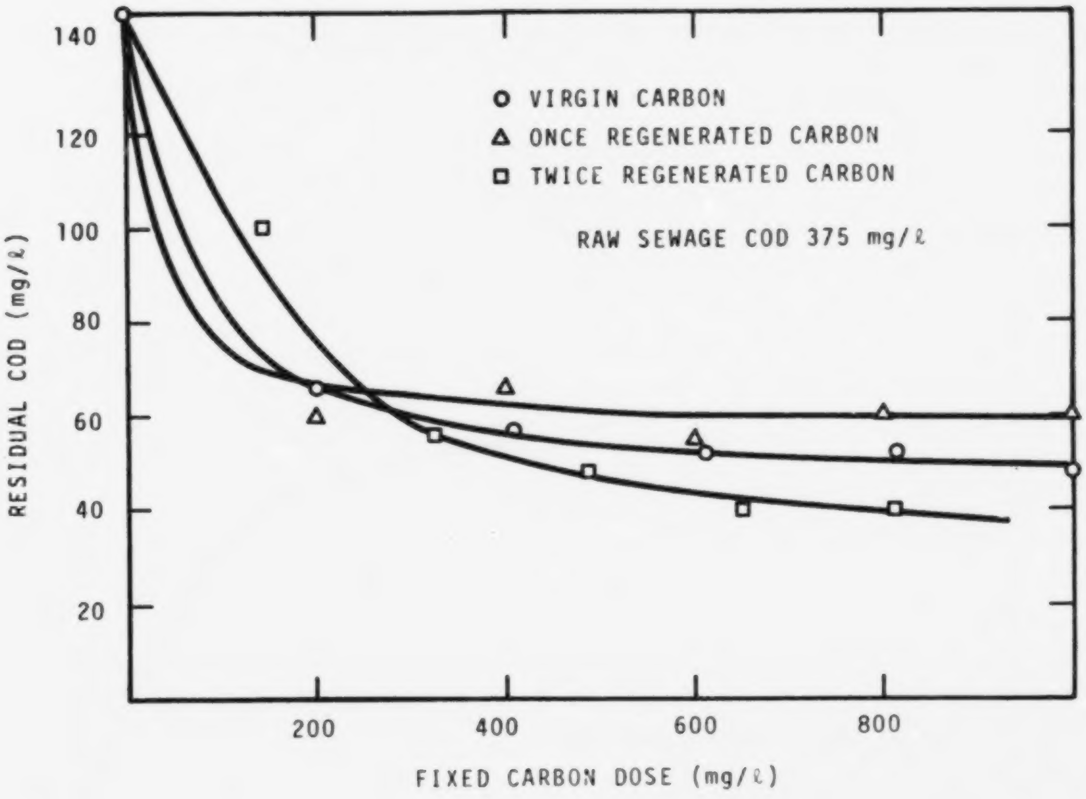


FIGURE 70. JAR TESTS ON ONCE AND TWICE REGENERATED CARBON - BATCH C

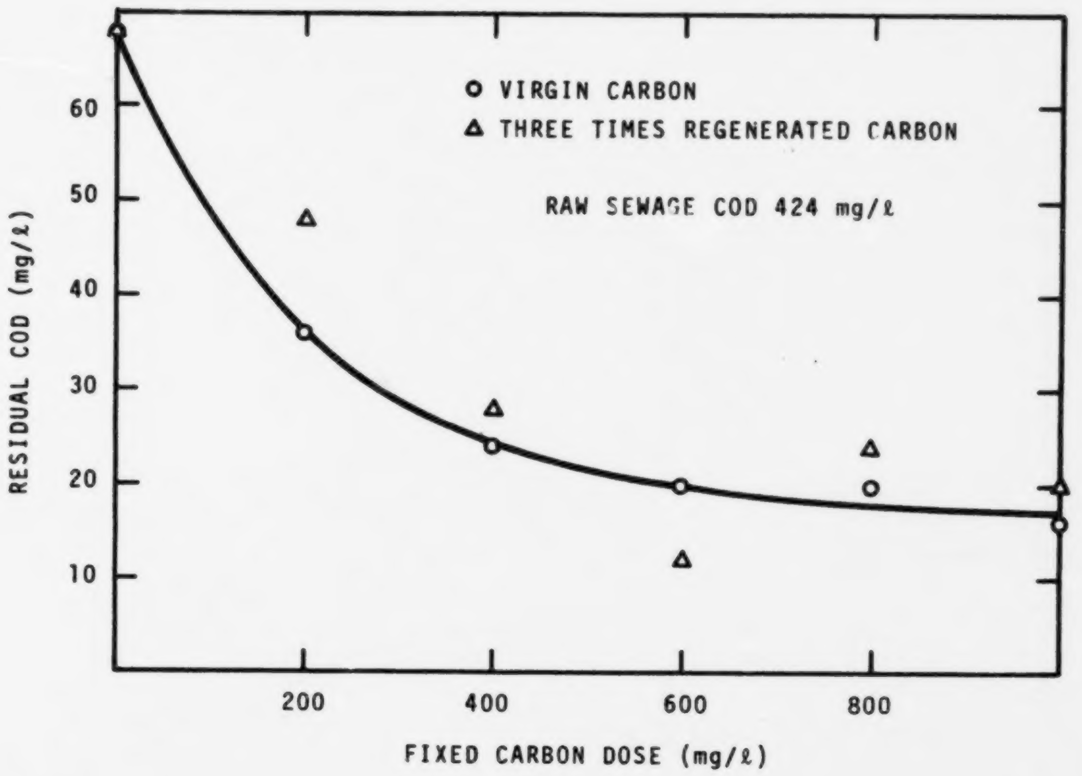


FIGURE 71. JAR TESTS ON THREE TIMES REGENERATED CARBON - BATCH C

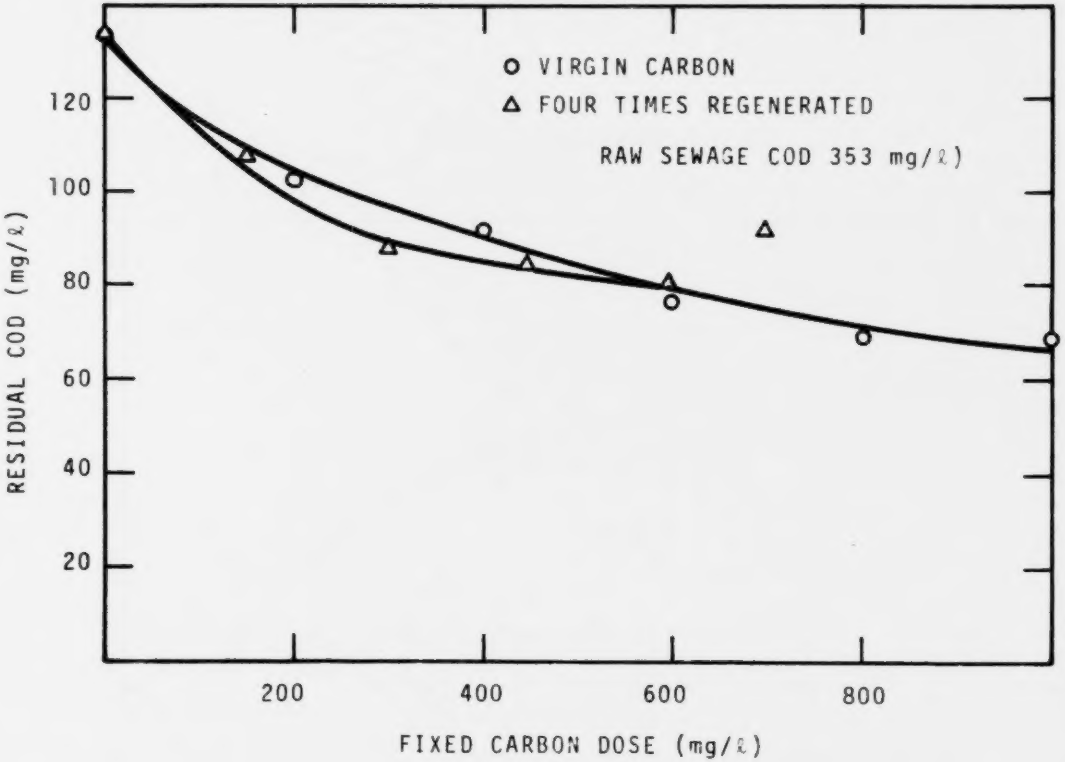


FIGURE 72. JAR TESTS ON FOUR TIMES REGENERATED CARBON - BATCH C

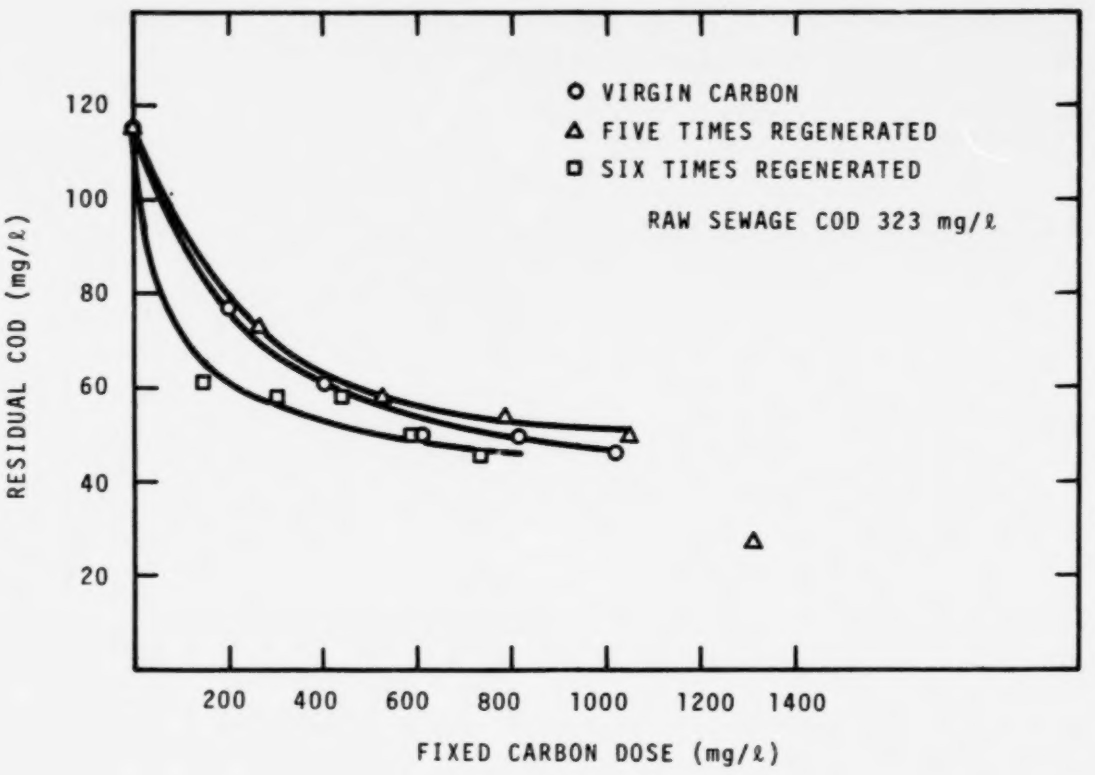


FIGURE 73. JAR TESTS ON FIVE AND SIX TIMES REGENERATED CARBON - BATCH C

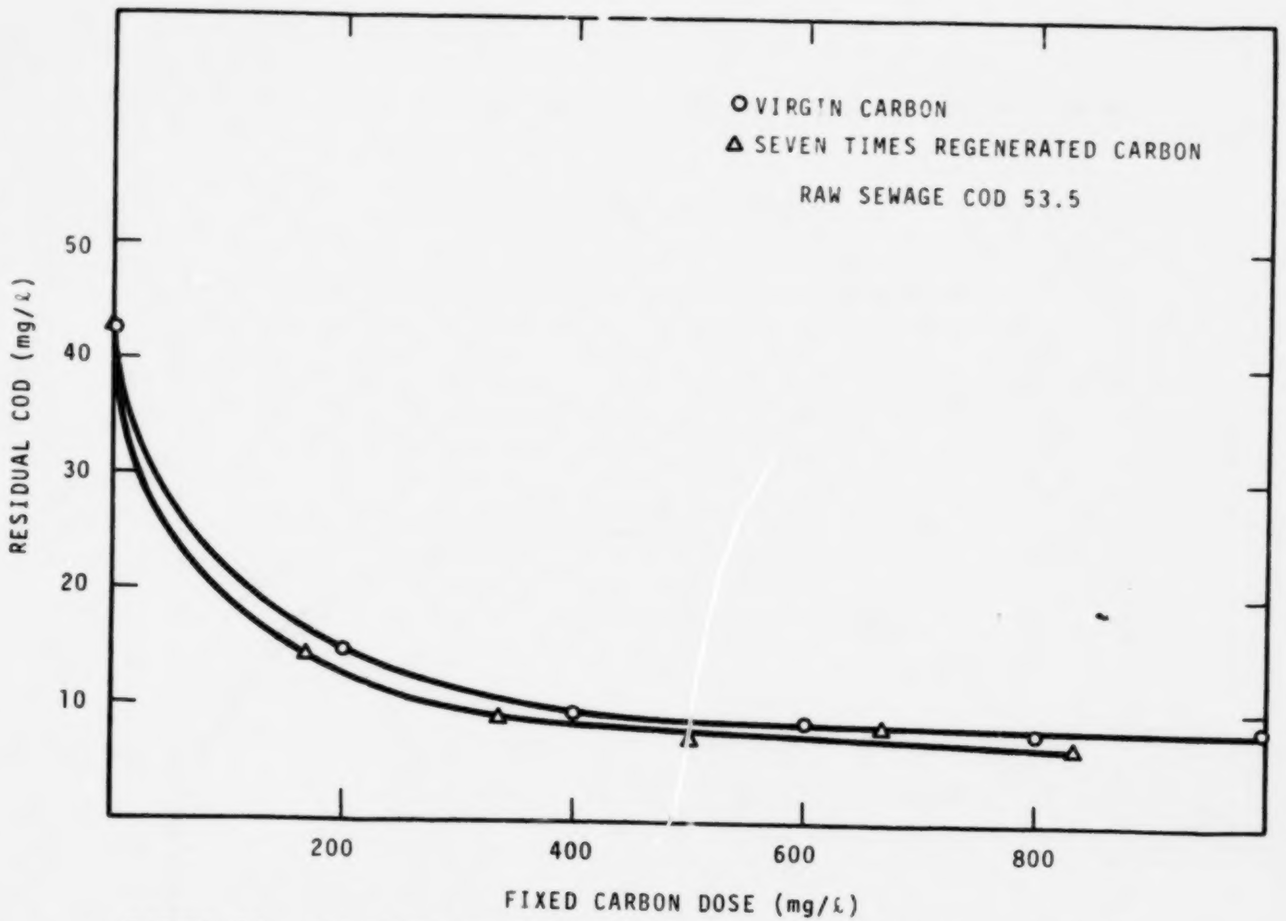


FIGURE 74. JAR TESTS ON SEVEN TIMES REGENERATED CARBON - BATCH C

In the pilot operations, alumina was conveyed from the furnace with the carbon and deposited in the storage tanks. Following the carbon regeneration operation, the carbon slurry was acidified to pH 2 with sulfuric acid in order to dissolve the alumina and free aluminum ion. The average recovery of aluminum was determined to be 91.3 percent per regeneration cycle in the 1972 pilot runs.

The aluminum mass balances for each of the Batch C regenerations are summarized in Table 11. Aluminum losses ranged from 2.8 percent to 21.4 percent per cycle and averaged 8.7 percent during this series of runs. Percentage loss was calculated from the carbon loss equation presented earlier.

As can be seen from Figure 75, the aluminum/carbon ratio of the regenerated slurry built up far beyond 0.027, the level necessary for proper flocculation in the treatment process. Excess alum was accidently added following the first and third regeneration cycles accounting for a major part of the Al/C ratio increases following these points. Another source of alum was makeup carbon to which was added 0.027 lbs Al per lb carbon.

During the pilot runs, acidification of the regenerated carbon-aluminum oxide slurry was carried out in 500 gallon tanks. Sulfuric acid was added to the slurry which was rapidly mixed and then a sample was withdrawn for a pH determination. Additional acid was then added if required. Using this method, sulfuric acid requirements averaged 0.63 lbs H_2SO_4/ lb carbon.

The acid usage during each regeneration cycle is shown in Table 5 and Figure 76. Acid requirements for regenerated carbon are higher than for virgin carbon as is expected since more acid soluble species exist in the regenerated slurry. It appears that after one or two cycles, the acid requirement is basically constant.

It was apparent that an excess of sulfuric acid was used in the pilot studies because the method of acidification did not lend itself to exact control of chemical dose. If an acidification technique utilizing more exact pH control were employed, it should be possible to substantially reduce the acid requirement. Laboratory titrations of the regenerated carbon slurries from the pilot operations indicate that it should be possible to reduce the sulfuric acid usage to 0.5 lbs H_2SO_4/lb carbon.

STACK GAS SAMPLING

A stack sampling program was undertaken by the New York State Department of Environmental Conservation, Division of Air Resources. All sampling was performed according to the

TABLE 11

ALUMINUM MASS BALANCE SUMMARY

Regeneration Number	7	8	9	10	11	12
Aluminum at End of Previous Regeneration (lbs)	0	20.5	19.7	31.3	31.1	25.6
Virgin Aluminum Added at End of Previous Regeneration (lbs)	28.0	7.5	16.8	13.5	0	0
Physical Losses in Treatment System (lbs)	1.9	7.7	2.3	12.8	1.8	3.1
Aluminum Fed to Regeneration Furnace (lbs)	26.1	20.3	34.2	32.0	29.3	22.5
Aluminum Recovered at End of Regeneration (lbs)	20.5	19.7	31.3	31.1	25.6	18.3
% Aluminum Loss in Furnace	21.4	3.0	8.5	2.8	12.6	18.7

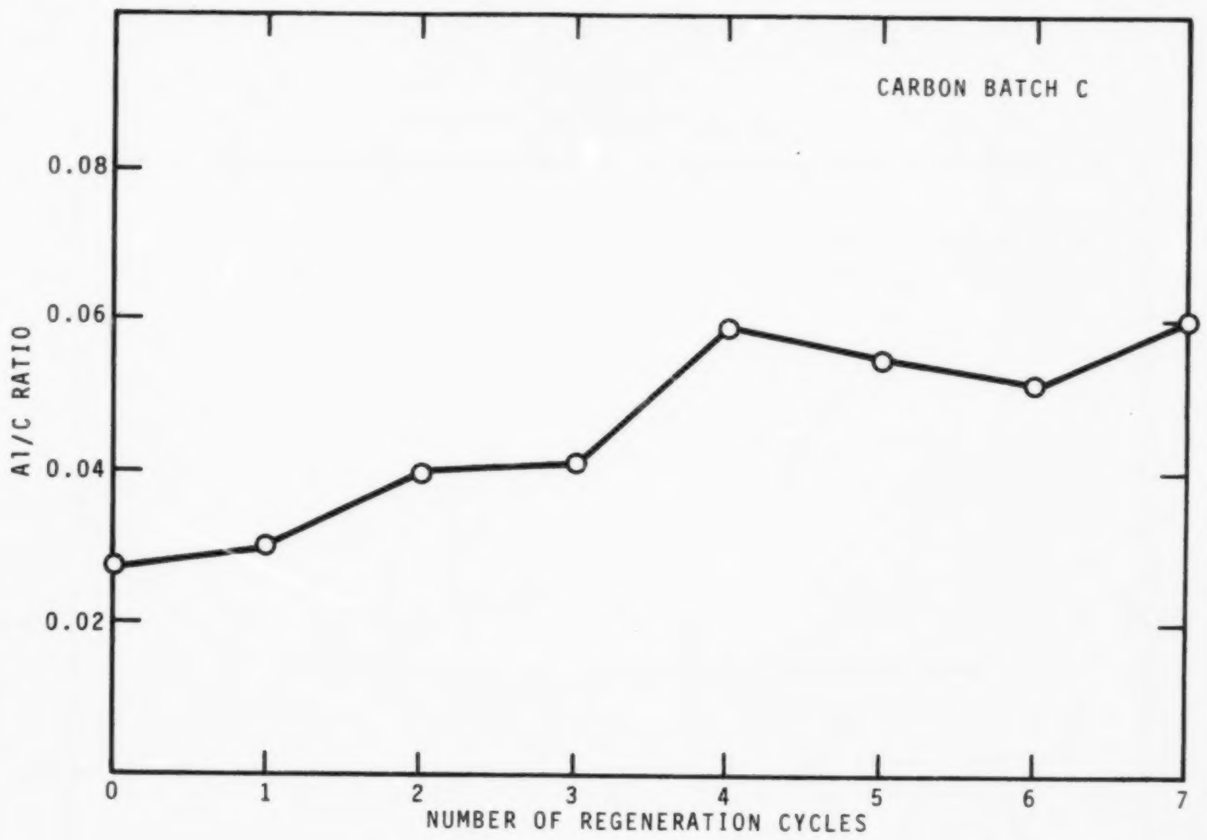


FIGURE 75. ALUMINUM BUILDUP IN REGENERATED CARBON

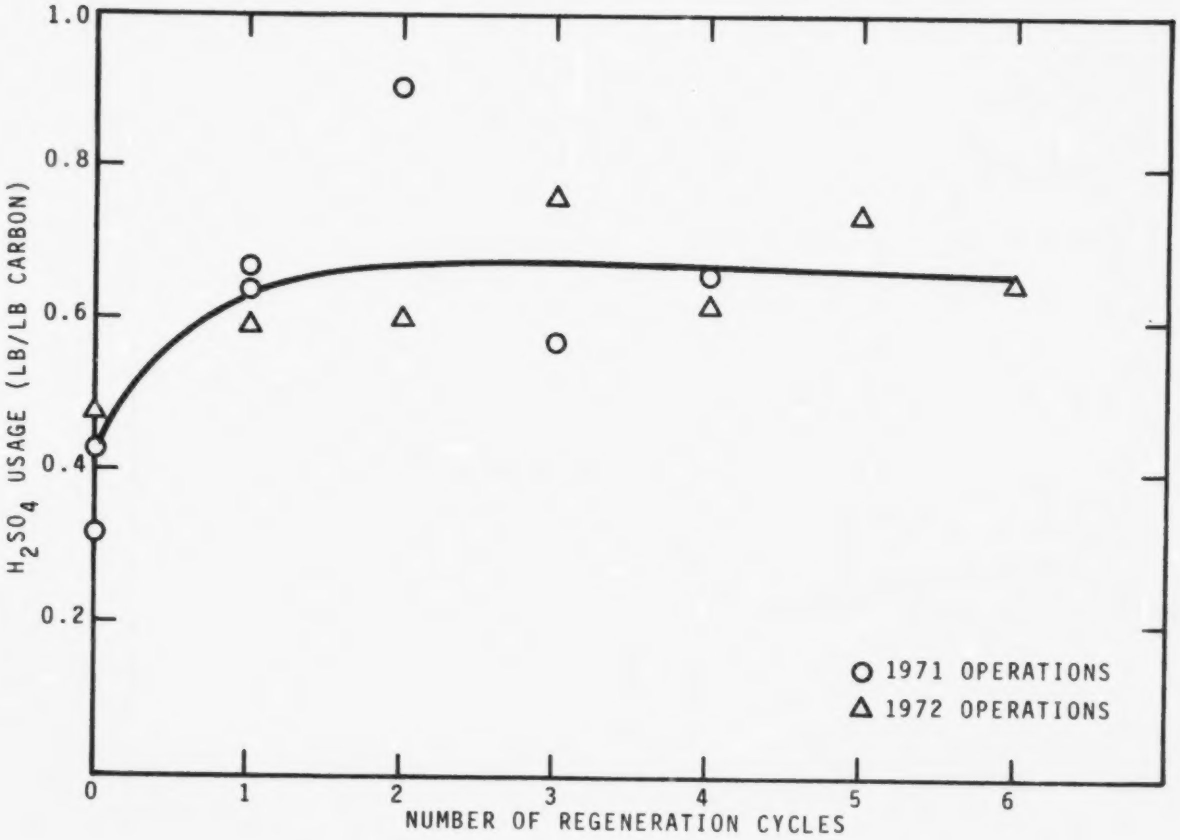


FIGURE 76. ACID USAGE DURING REGENERATION STUDIES

EPA sampling method published in the December 23, 1971 Federal Register. Tests were performed for nitrogen oxides, sulfur oxides, water vapor, particulates, and trace metals.

Nitrogen oxide analyses were conducted on 5/9/72 using a chemiluminescent analyzer. During the test the firebox and bed temperatures were 1780-1810°F and 1200-1300°F, respectively. The NO stack gas content was 48-50 ppm and the NO_2 concentration was 1-3 ppm.

The stack gas opacity was estimated to be 10-20 percent. This was due to a large amount of steam and powdered carbon in the stack gas at the time.

Samples for SO_2 analysis were collected on 6/13/72. No SO_2 was detected in the samples.

Stack samples for particulates, moisture content and trace metals were collected 6/12-13/72. The results are presented in Table 12. Particulate emissions are of major concern not only because of the air pollution potential but because of the loss of regenerated carbon which they represent. The relatively high particulate emissions in the stack gas occurred as a consequence of the wrong size venturi being supplied in the scrubber system. Particle capture is a function of the velocity through the venturi throat. Since the venturi throat was oversized in the pilot system, particle capture was not highly efficient. As can be seen from inspection of the data of Table 12, during sampling runs 1 & 2 when the pressure drop across the venturi was 3.5-4 inches of water, 1.8 to 1.5 percent of the carbon product was lost. However, during run 3 when the pressure drop was increased to 8.5 inches of water, the carbon loss was correspondingly decreased to 0.92 percent. Venturi manufacturers guarantee that with a pressure drop of 20 inches of water, the maximum particulate loss will be 0.078 lb/hr, which corresponds to 0.67 and 0.54 percent carbon losses for runs 1 and 3, respectively. Since most of the furnace operation time was at the conditions of run #1, the recoverable loss from the stack was approximately 1 percent of the total carbon.

The carbon fraction in the stack gas particulates could not be determined and therefore, the carbon/inert ratio in the regenerated slurry was used to calculate stack carbon losses. This will obviously underestimate the carbon loss since the ash was mostly fine sand from the fluidized bed which is much more readily captured by the cyclone type separator. Since the ash content of the stack particulates should be much lower than the recovered carbon, the amount of carbon recoverable with a properly designed scrubber system is estimated conservatively.

TABLE 12

STACK SAMPLING DATA

Sample Number	1	2	3
Bed Temperature, °F	1230	1250	1250
Firebox Temperature, °F	1830	1860	1840
Bed Velocity, ft/stc	1.7	1.7	2.2
Sludge Feed rate, lbs/hr	80	90	100
Volume Sampled, scf	43.3	56.2	66.0
Moisture Content, %	37.2	44.1	51.4
Total Particulates, lb/hr	0.213	0.195	0.189
Carbon, % of carbon feed to furnace	1.84	1.50	0.92
Iron, lbs/hr	0.00402	0.00313	0.000725

Thus installation of the proper sized venturi should substantially reduce carbon losses in the stack gases below the measured levels.

CARBON REGENERATION STUDIES

The recovery of carbon from the regeneration furnace was calculated on the basis of a fixed carbon mass balance over the whole pilot plant. The average carbon recovery over the first four cycles was 89 percent per cycle.

Table 13 shows the breakdown of the carbon mass balance during the 1972 portion of the study. The carbon loss during the period ranged from 1.3 percent to 22.3 percent. The average loss per cycle calculated on an overall basis was 9.7 percent. Percentage loss was calculated by the equation

$$\%\ \text{Loss} = \frac{\text{Fixed Carbon Consumed} - \text{Physical Losses} - \text{Fixed Carbon Recovered}}{\text{Fixed Carbon Consumed} - \text{Physical Losses}}$$

Overall loss per cycle was determined by dividing the percentage loss determined as in the above equation by the total number of regeneration cycles.

This method of loss calculation assumes that all physical losses occurred during the sewage treatment portion of the pilot plant operation, prior to regeneration. Since small losses did occur after regeneration, the percentage loss figures calculated for each cycle are slightly higher than actual.

Carbon loss in the stack gas could not be routinely determined and therefore, is not included in Table 13. As previously discussed, the recoverable loss from the stack at typical regeneration conditions was found to be approximately 1 percent of the carbon entering the furnace. The remainder of the carbon loss is attributed to burning in the fluidized bed. The carbon burned during regeneration is thus calculated to be an average of 8.7 percent of the carbon entering the furnace.

Determination of ash buildup as the carbon was repeatedly regenerated was complicated by the fact that some sand was carried over from the furnace and contributed to the apparent "ash" content. Sand carryover from the furnace was collected with the regenerated carbon in the scrubber stream. A portion of this sand was separated from the carbon slurry in the small settling chamber ahead of the carbon storage tanks. During runs 11 and 12 the average amount of sand collected in this manner was 0.27 pounds per pound of carbon recovered. A significant quantity of sand

TABLE 13

CARBON MASS BALANCE SUMMARY

Regeneration Number	7	8	9	10	11	12
Fixed Carbon at End of Previous Regeneration, (lbs)	--	687	499	828	504	468
Fixed Virgin Carbon Added at End of Previous Regeneration (lbs)	787	131	498	157	0	0
Physical Losses in Fixed Carbon in Treatment System (lbs)	73	227	55	*336	30	57
Fixed Carbon Fed to Regeneration Furnace (lbs)	714	591	942	649	474	411
Fixed Carbon Recovered at End of Regeneration Cycle (lbs)	687	499	828	504	468	356
% Carbon Loss in Furnace	3.8	15.6	12.1	22.3	1.3	13.4

---

*Approximately 300 pounds purposely wasted to reduce carbon inventory was not trapped in this manner and was cycled through the system with the carbon. Sieve analysis of the sand collected in the settling chamber is presented in Table 14. As would be expected the data show the sand to be very fine.

An efficient method of separating the fine sand and ash from the powdered activated carbon is desirable in order to reduce the amount of mass carried through the treatment and regeneration systems. A brief laboratory investigation was conducted to study the feasibility of classification of the carbon-inerts in the regeneration stream. Fifty milliter samples of the slurry from the seventh regeneration (Batch C) were centrifuged for five minutes at various speeds corresponding to radial accelerations up to 1350 gravities. The lower ten percent of the cake was then analyzed for inert content with results as follows:

Radial acceleration, gravities	0	50	330	750	1350
Solids content of lower tenth, %	34.4	40.2	46.8	45.3	47.0
Inert content of lower tenth, %	52.2	70.3	78.5	78.3	77.7

The data show that at accelerations greater than 330 gravities a cake is attainable which contains approximately 46 percent solids of which 78 percent is inert material. If this fraction were wasted for blowdown, less than 22 percent of the blowdown would be carbon thus effecting a substantial savings in carbon loss. In addition, if the slurry were acidified prior to the inert carbon classification, the loss of alum in the blowdown would be reduced to only that portion dissolved in the wasted slurry.

Based on these results, it appears that classification would be feasible and could lead to reductions in operating costs by reducing the carbon and aluminum lost to blowdown.

A number of factors must be considered in selecting the rate of blowdown. At a particular blowdown rate, the inert material will eventually reach an equilibrium concentration. This inert fraction will be cycled through the treatment system, dewatered, and passed through the regeneration system. The costs associated with these operations increase in proportion to the quantity of inert material carried. However, a high rate of blowdown which would minimize the quantity of inerts would increase carbon losses. Therefore, blowdown should be selected to minimize operating costs.

Based on the design and operating parameters presented in Section VIII of this report, the effect of blowdown rate on total treatment costs was calculated. Two cases were assumed: no classification and classification to achieve a blowdown

TABLE 14

SIEVE ANALYSIS OF FLUIDIZED BED SAND COLLECTED WITH REGENERATED CARBON

Mesh	Weight Retained (g)	Fraction Retained (%)
40	0.73	1.66
50	.42	0.96
60	.45	1.02
70	.40	.91
100	5.20	11.83
150	7.84	17.84
200	20.22	46.01
Pan	8.69	19.77
	43.95	100.00

stream containing 78 percent inerts. The results are presented in Figure 77. It is evident that classification would significantly reduce treatment costs at optimum blowdown rates. In the case of no classification, optimum blowdown would be 5 percent while with classification optimum blowdown would be 6.5 percent.

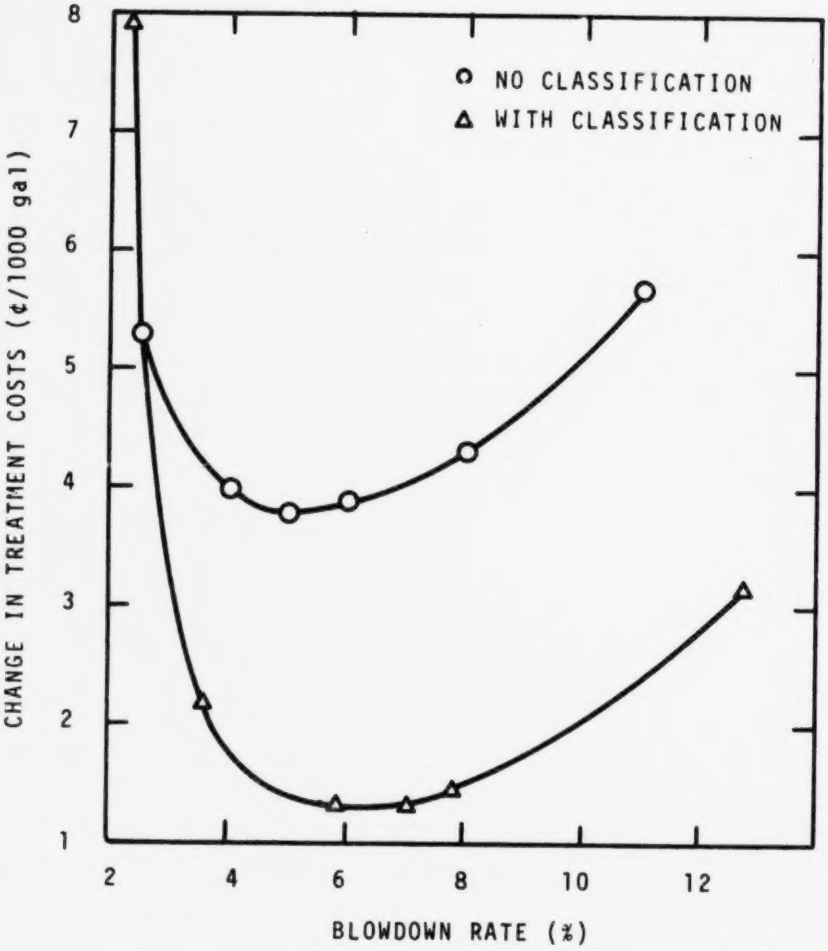


FIGURE 77. EFFECT OF BLOWDOWN RATE ON TREATMENT COSTS FOR A 10 MGD PLANT

SECTION VIII

DESIGN AND ECONOMIC CONSIDERATIONS

Based upon the data evolved in the Albany pilot plant studies, preliminary estimates relating to design parameters and the corresponding capital and operating costs for a 10 mgd treatment plant have been developed. A conservative approach was adopted in the development of these estimates and therefore, they should represent a "worst case" -- the maximum probable costs -- for a 10 mgd plant utilizing the powdered carbon treatment process described in this report. For example, the tube settler loading rate utilized in developing the capital cost estimates was the loading rate actually used in the pilot studies. The pumping capacity of the pilot system and the operational problems associated with the pilot tube settler prohibited investigation of any higher loading rates. It is probable that in a commercial unit the loading rate could be increased substantially which would result in a reduction in capital costs. Therefore, further process development should lead to a downward adjustment of capital and operating cost projections.

Several major questions with regard to design of a commercial fluidized bed carbon regeneration furnace require resolution before an optimum, minimum cost system can be designed. If combustion could be carried out directly within the fluidized bed chamber, the required unit area would be halved, the size of the scrubber would be halved, and there would be no requirement for a recycle blower. However, this method of operation might result in greatly increased carbon losses through combustion. At Albany, combustion was accomplished in a chamber underneath the hearth and temperatures were reduced to a practical limit by off gas recycle. This latter approach should be feasible for a commercial unit. However, there is a practical upper limit to the size of a brick hearth which could be constructed. Moreover, the combustion chamber temperature cannot be raised above an upper limit of 2000°F.

A substantial savings in capital and operating costs can be realized if off gases are not recycled. The pilot program utilized recycle, but earlier work by Battelle-Columbus(12) indicated it may not be required.

Other potential cost savings lie in the area of waste heat utilization. Conceivably, waste heat from the regeneration furnace could be used to dry the sludge before regeneration. This would result in capital cost savings since a smaller size furnace would be required. In addition, fuel requirements would be reduced thus resulting in reduced operating costs.

Classification of the carbon and inert fractions in the regenerated stream prior to blowdown would reduce makeup carbon and alum requirements below those utilized for cost projections in the current analysis.

For purposes of this report, two sets of conditions (off gas recycle and no recycle) have been assumed and capital and operating costs have been calculated for each case. Costs have been developed both for operation as municipal wastewater and combined sewage treatment plants with two configurations for each plant type.

SYSTEM DESIGN PARAMETERS

The design parameters used in developing the treatment system capital cost estimates are given in Table 15.

SYSTEM CAPITAL COSTS

Capital costs are based on vendor information, published cost data(12,13,14), and engineering estimates of the required equipment sizes. Capital cost estimates for municipal wastewater and combined sewage treatment are given in Table 16.

SYSTEM OPERATING PARAMETERS

Table 18 presents the system operating costs based on the parameters presented in Table 17.

TOTAL SYSTEM COSTS

Total system costs include the operating costs given in Table 18 plus amortization of the capital costs presented in Table 16. Amortization costs were calculated at 6 percent over 25 years. The total system costs are presented in Table 19.

TABLE 15

SYSTEM DESIGN PARAMETERS

Treatment System	
Carbon Contact	
Time at pH 4	10 minutes
Time at pH 7	5 minutes
Flocculation	
Velocity Gradient	75 fps/ft
Time	10 minutes
Tube Settler Loading Rate	2880 gpd/ft^2
Filter	
Length of Filter Run	12 hours
Loading Rate	5 gpm/ft^2
Chlorine Contact Time	10 minutes
Chemical Storage Capacity	12 hours
Sludge Storage	1 day

Regeneration System	With gas recycle	Without gas recycle
Combustion Chamber Temperature, °F	2000	2000
Bed Temperature, °F	1250	1250
Fluidizing Gas Velocity, ft/sec	1.3	1.0
Heat Requirement, million BTU/hr	30.7	24.5
Bed Diameter, 2 units, each, ft	21.7	19.8
Blowdown, %	5	5

TABLE 16

CAPITAL COST ESTIMATES FOR 10 MGD MUNICIPAL WASTEWATER AND STORM WATER TREATMENT PLANTS

Item	Municipal Plant Installed Costs, $	Storm Water Plant Installed Costs, $
Screens, grit chamber, overflow	10,000	10,000
Reaction vessels	27,000	27,000
Chemical storage tanks	32,000	32,000
Carbon slurry tanks	40,000	40,000
Sludge storage	17,800	17,800
Pumps	35,000	35,000
Agitators	45,700	45,700
Flocculation, sedimentation	475,000	475,000
Filtration	300,000	---
Chlorination	14,700	14,700
Centrifuge	80,000	80,000
Sludge pumps	53,700	53,700
Regeneration facility		
With gas recycle	1,104,000	---
Without gas recycle	794,800	794,800
Subtotals		
With gas recycle	2,234,900	---
Without gas recycle	1,925,700	1,625,700
Without regeneration	---	830,900
Total Capital Costs*		
With gas recycle	2,462,390	---
Without gas recycle	2,121,270	1,791,270
Without regeneration	---	966,990

*Contingencies 10%
Land, 1.5 acres @ $2000/acre

TABLE 17

SYSTEM OPERATING PARAMETERS

	MUNICIPAL PLANT	STORM WATER PLANT	
ITEM		With Regeneration	Without Regeneration
Treatment System			
Carbon dose, mg/l	600	400	400
Alum dose, mg/l	200	200	200
Polyelectrolyte dose, mg/l	2.0	2.0	2.0
Lime dose, mg/l	150	150	---
Sulfuric acid, #/# carbon	0.5	0.75	---
Sludge dewatering polyelectrolyte dose, #/ton dry solids	1	1	1
Regeneration System			
Carbon recovery, %	91	91	0
Alum recovery, %	91	91	0
Blowdown, %	5	5	100
Carbon feed rate, #/hr	2080	1390	---
Sludge feed rate, #/hr	21,800	21,800	---
Sludge solids content, %	22	22	---
Sludge inerts content % on dry basis	60	60	---
Fuel, ¢/MBTU	25	25	25
Power, ¢/kwhr	0.7	0.7	0.7
Blowdown disposal cost, ¢/lb solids	0.4	0.4	0.4

TABLE 18

OPERATING COST ESTIMATES FOR 10 MGD MUNICIPAL WASTEWATER AND STORM WATER TREATMENT PLANTS

ITEM	MUNICIPAL	STORM WATER	
	With Regeneration ¢/1000 gal	With Regeneration ¢/1000 gal	Without Regeneration ¢/1000 gal
Sulfuric acid	4.3	4.3	0
Lime	0.8	0.8	0
Make-up alum	0.7	0.7	5.0
Polyelectrolyte[1]	2.9	2.9	2.9
Make-up carbon	6.3	4.2	30.1
Carbon regeneration[2]			
With gas recycle	3.5	---	0
Without gas recycle	2.9	2.9	0
Blowdown Disposal	0.2	0.2	0
Chlorination	0.2	0.2	0.2
Power	0.2	0.2	0.2
Labor, 60 hr/day @ $4.00/hr	2.4	2.4	1.6[3]
TOTAL			
Regeneration with gas recycle	21.5		
Regeneration without gas recycle	20.9	18.8	
Without regeneration			42.9

---

[1] Includes dewatering dose

[2] Includes fuel costs

[3] 40 hr/day

TABLE 19

TOTAL COSTS FOR 10 MGD MUNICIPAL WASTEWATER AND STORM WATER TREATMENT PLANTS

PLANT DESCRIPTION	OPERATING COST ¢/1000 gal	AMORTIZATION COST ¢/1000 gal	TOTAL ¢/1000 gal
Municipal, with gas recycle	21.5	5.11	26.6
Municipal, without gas recycle	20.9	4.58	25.5
Storm, without regeneration	42.9	1.84	44.7
Storm, regeneration without gas recycle	18.8	3.43	22.2

SECTION IX

ACKNOWLEDGMENTS

The authors wish to extend their gratitude to the many people whose assistance was necessary to the timely and successful completion of this program. A. T. Brix, J. J. Dorgan, and J. Green made significant contributions to the pilot plant design. R. G. Parkhurst and M. J. Mason contributed significantly of their own time during the pilot plant shakedown at Richland. Battelle's operating crew at Albany, J. A. Coates, M. J. Mason, R. G. Swank, and R. G. Upchurch invested many long hours in keeping the plant operating and contributed in large part to the success of the Albany demonstration. Other Battelle personnel who contributed advice, suggestions, time, and moral support throughout the course of this program include B. W. Mercer and D. E. Olesen. Former Battelle personnel who also fall in this category are Dr. C. J. Touhill and Mr. G. L. Culp.

Mr. Danforth Bodien and Mr. Frank Condon of the Environmental Protection Agency provided support and assistance throughout the course of this program.

Nichols Engineering and Research Corporation designed and supplied the fluidized bed pilot regeneration furnace used in the study. Mr. Charles von Dreusche, Jr. provided much assistance in overcoming problems with the unit and developed much of the furnace cost data used in this report. Mr. George Nowowiejski, also of Nichols, invested much time and effort during the shakedown of the furnace.

Dr. Leo Hetling of the New York State Department of Environmental Conservation provided assistance in locating and obtaining the Albany site. He also provided help in numerous ways throughout the operations at Albany and has initiated studies by the New York State Department of Environmental Conservation to characterize the Island Creek Drainage Area.

Mr. Walter Connley of Neptune Microfloc, Inc., provided cost information used in this report.

Preceding page blank

SECTION X

REFERENCES

1. "Problems of Combined Sewer Facilities and Overflows." *Federal Water Pollution Control Administration*, U. S. Department of Interior, WP-20-11. 1967.

2. Weibel, S. R., Anderson, R. J., and Woodward, R. L. "Urban Land Runoff as a Factor in Stream Pollution." *J. Water Pollution Control Federation*, Vol. 36, pp. 914-924. 1964.

3. Burns, R. J., Krawczyk, D. F., and Harlow, G. L. "Chemical and Physical Comparison of Combined and Separate Sewer Discharges." *J. Water Pollution Control Federation*, Vol. 40, pp. 112-126. 1968.

4. "Water Pollution Aspects of Urban Runoff." *Federal Water Pollution Control Administration*, U. S. Department of Interior, WP-20-15. 1969.

5. Shuckrow, A. J., Dawson, G. W., and Olesen, D. E. "Treatment of Raw and Combined Sewage." *Water and Sewage Works*, pp. 104-111. April 1971.

6. Rizzo, J. L. and Schade, R. E. "Secondary Treatment with Granular Activated Carbon." *Water and Sewage Works*, p. 307. 1969.

7. Weber, W., Hopkins, C. B. and Bloom, R. "Physiochemical Treatment of Wastewater." *Journal Water Pollution Control Federation*, p. 83. 1970.

8. Zuckerman, M. M. and Molof, A. H. "High Quality Reuse Water by Chemical-Physical Wastewater Treatment." *Journal Water Pollution Control Federation*, p. 437. 1970.

9. Shuckrow, A. J., *et al*. "A Pilot Study of Physical-Chemical Treatment of the Raw Wastewater at the Westerly Plant in Cleveland, Ohio." A paper presented at the International Association on Water Pollution Research Workshop, Vienna, Austria. September 1971.

10. "Standard Methods for the Examination of Water and Wastewater." Twelfth and Thirteenth Editions, APAA, AWWA, WPCF. 1967 and 1971.

Preceding page blank

11. Berg, E. L., *et al*. "Thermal Regeneration of Spent Powdered Carbon Using Fluidized-Bed and Transport Reactors." Chemical Engineering Progress Symposium Series No. 107, Vol. 67. 1971.

12. "The Development of A Fluidized Bed Technique for the Regeneration of Powdered Activated Carbon." *Water Pollution Control Research Series*, ORD-17070FBD03/70, Federal Water Quality Administration. 1970.

13. Culp, R. L. and G. L. Culp. "Advanced Wastewater Treatment." Van Nostrand Reinhold, 1971.

14. Guthrie, K. M. "Capital Cost Estimating." *Chem. Engr.*, Vol. 76, No. 6. March 24, 1969.

SECTION XI

APPENDIX A

LABORATORY STUDIES

An extensive laboratory program to develop and establish the feasibility of the physical-chemical treatment process described in this report was carried out from July 1969 through March 1970. The results of this laboratory program are described below.

GENERAL

Influent to the Richland, Washington, sewage treatment plant was used in all of the laboratory work. At the outset of the investigation, an extensive analytical study to characterize Richland sewage was carried out in order to investigate the suitability of this influent for use in the laboratory studies on the treatment process. Grab samples were obtained at various times of the day over a 3-1/2 day period and were analyzed for various constituents in accordance with the procedures outlined in "Standard Methods(10). Ca and Mg concentrations were determined by atomic absorption techniques. The results of the characterization are presented in Table A-1.

During the course of the research, a Beckman Model 915 Total Organic Carbon Analyzer was obtained and when this instrument became operational, TOC measurements were substituted for COD determinations.

A bench scale continuous flow system was constructed early in the program. As the work progressed, this system was modified several times to incorporate features such as in-line mixing and pH control. Two basic types of clarifiers were employed in this system: a tube settler and an upflow clarifier. Upon selection of tube settlers for the pilot plant, all further bench scale work was conducted with the laboratory tube settler. Figure A-1 is a schematic diagram of the final laboratory system.

CARBON STUDIES

Aqua Nuchar A was selected for use in initial studies based on its relatively low cost and satisfactory performance in prior studies. Several sets of experiments were conducted to examine the sorption characteristics of the powdered carbon. In order to accomplish this, 300 ml aliquots of fresh Richland influent were placed in 8 oz polyethylene

TABLE A-1

COMPOSITION OF RICHLAND SEWAGE

Time of Day	0700	1130	1620	1930	2340
Conductivity (μmhos/cm)	950-620 750-6	1600-820 1080-4	460-400 430-3	532-460 490-3	590-540 567-3
pH	7.68-7.47 7.56-6	7/72-7.60 7.69-4	7.48-7.36 7.42-3	7.36-7.30 7.33-3	7.38-7.31 7.34-2
Temp °C	22-20 21-2	26-25 25.5-2	26 26-2	24-22 23-2	24-23 23.5-2
Turb (JTU)	28-10 19-2	105-68 87-2	130-90 110-2	150-55 103-2	160-58 109-2
Alkalinity (mg/l as $CaCO_3$)	252-199 239-6	325-297 310-4	264-224 248-3	254-229 248-3	277-253 267-3
Ca (mg/l)	43-36 40-4	45-38 41-3	41-38 40-3	44-36 40-3	45-43 44-2
Mg (mg/l)	13-10 11.5-4	15-10 12-3	12-9 10-3	12-8 11-3	12 12-2
COD (mg/l)	160-130 142-6	544-436 503-4	525-267 351-3	525-303 401-3	450-400 431-3
NH_4-N (mg/l)	20.7-10.8 15.3-6	44.8-32.7 39.4-4	19.9-14 17-3	17.5-13.2 15.5-3	21.8-18.3 20.1-3
NO_2-N (mg/l)	.22-.01 .067-5	.025-.01 .019-4	.01-0 .003-3	.025-0 .012-3	.025-0 .012-3

(continued)

TABLE A-1 (continued)

COMPOSITION OF RICHLAND SEWAGE

Time of Day	0700	1130	1620	1930	2340
NO_3-N (mg/l)	3.2-0 .66-6	.15-.10 .11-4	.02-0 .007-3	.2-0 .13-3	.2-0 .1-3
Org. N	17.1-6.7 11.6-6	31.7-12.6 21-4	12.6-10.2 11.8-3	13.9-9.4 11.6-3	12.5-11.7 12.2-3
Sol PO_4 (mg/l)	41-20 30.1-6	34-27.5 31-4	50-26.5 38.8-3	34.5-30.5 33.3-3	37.5-31.5 35.1-3
TS (mg/l)	1080-510 705-6	894-694 764-4	735-636 685-2	724-672 701-3	770-685 721-3
TVS (mg/l)	261-168 204-6	474-329 400-4	303-234 294-3	454-319 375-3	450-363 418-3
SS (mg/l)	124-51 93-5 93-5	320-228 274-4 274-4	286-198 219 219-3	315-168 232-3	275-165 211-3
VSS (mg/l)	92-30 60-5	208-176 188-4	164-122 139-3	182-103 151-3	203-112 173-3
Settleable Solids (ml/l)	4.0-3.5 3.7-3	15-11.5 13-3	9-5 7.1-3	17-5.5 9.8-3	8-7 7.3-3
Settleable Solids (mg/l)	145-82 114-2	315-148 232-2	180-52 116-2	278-112 204-3	191-164 178-2

NOTE: Numbers for each time period represent: $\left\{\begin{array}{l}\text{high value - low value}\\ \text{average - no. of samples}\end{array}\right\}$

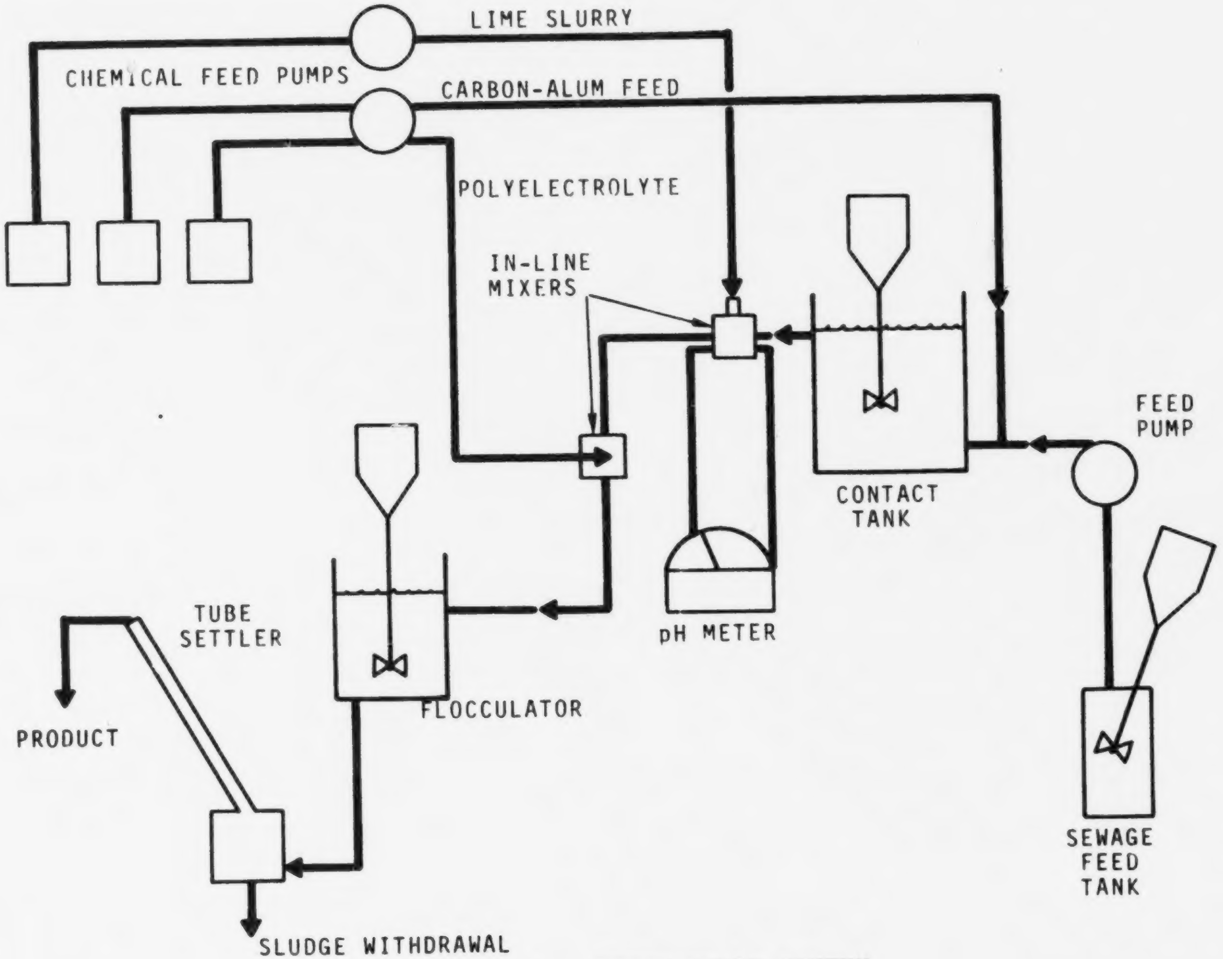

LIME SLURRY
CHEMICAL FEED PUMPS
CARBON-ALUM FEED
POLYELECTROLYTE
IN-LINE MIXERS
FEED PUMP
CONTACT TANK
pH METER
TUBE SETTLER
FLOCCULATOR
PRODUCT
SEWAGE FEED TANK
SLUDGE WITHDRAWAL

FIGURE A-1. BENCH SCALE SYSTEM

bottles and a quantity of powdered carbon was added to each bottle. The set of samples was then placed on a mechanical shaker and was agitated overnight. This was believed to be a sufficient period in which to establish equilibrium conditions. Each carbon-sewage mixture was then filtered through a 0.45 μ membrane filter and the COD of the filtrate was determined. Figure A-2 contains the results for seven different sewage samples. It appears that sorption of COD is essentially complete at a carbon concentration of 800-1000 mg/l. Increasing the carbon concentration beyond this point has little or no effect on the residual COD. Two parallel sets were run in one instance in order to determine if the presence of bentonite had any effect on the sorption equilibrium. As seen from inspection of Figure A-2, 300 mg/l of bentonite had no noticeable effect on the equilibrium solution concentration of COD.

Sewage samples were contacted with 1000 mg/l of Aqua Nuchar A for various time intervals and were then centrifuged and finally filtered through 0.45 μ filters. COD analyses of the filtrate indicated that sorption was essentially complete after a contact period of ten minutes. Subsequent to these findings, a carbon concentration of 1000 mg/l and a contact time of ten minutes were adopted for experimental use.

Subsequent tests, run with 500 ml sewage aliquots and one hour contact times, suggested that TOC removal is virtually complete at a carbon dose of 500-600 mg/l. Data from these tests are presented in Figure A-3. In view of these findings, another series of tests to examine required detention time at the lower carbon dose was conducted. As can be seen from inspection of the data in Figure A-4, a ten minute detention time should be adequate even at this reduced carbon dose.

Subsequently, samples of fifteen different commercial grade powdered carbons were evaluated in a series of tests. Earlier comparisons showed little or no correlation between methylene blue adsorption and organic carbon removal. Hence, tests were based on residual organic carbon concentrations after both contact tests and jar tests.

Contact tests were conducted using 500 ml sewage samples dosed to 1000 mg C/l. Duplicate samples were prepared, one of which was shaken for an hour and the second for 21 hours. The samples were then filtered through 0.45 μ membrane filters and analyzed for total organic carbon. This procedure was repeated for seven of the carbons with a sewage sample obtained on a different day. The results of these runs are given in Table A-2.

Based on the results of the contact tests, selected carbon types from the different companies were used in jar tests. A carbon dose of 1000 mg/l was used with 350 mg/l alum

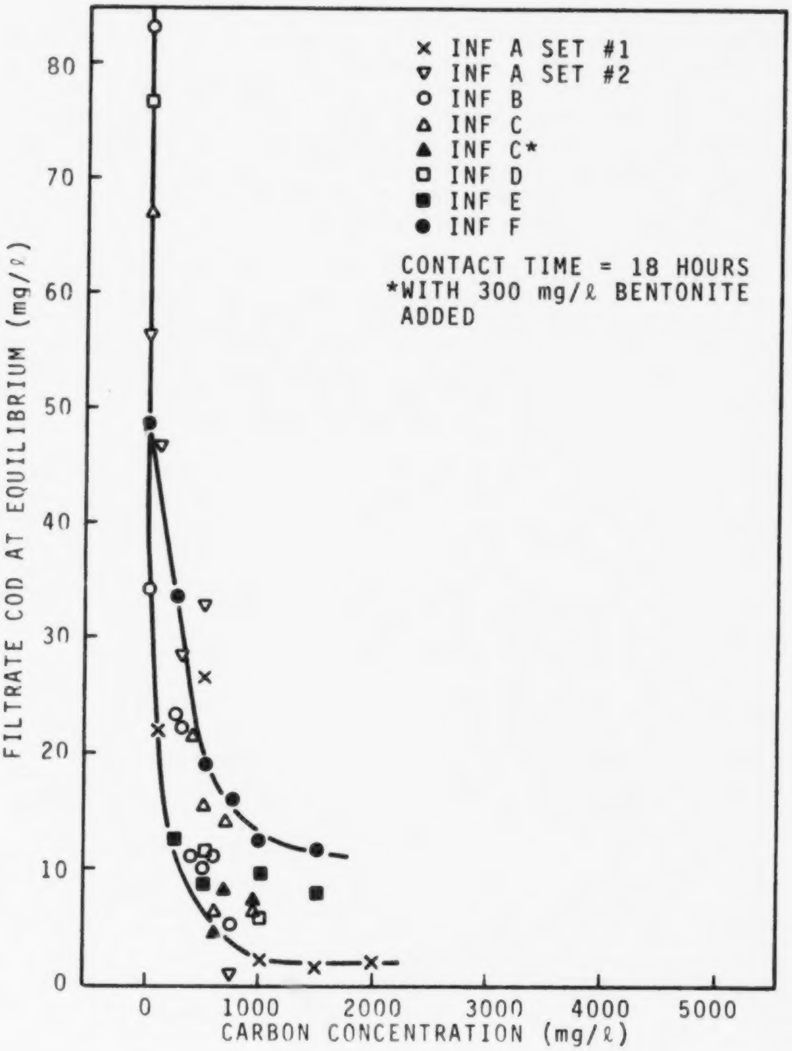


FIGURE A-2. EFFECT OF CARBON CONCENTRATION ON EQUILIBRIUM COD

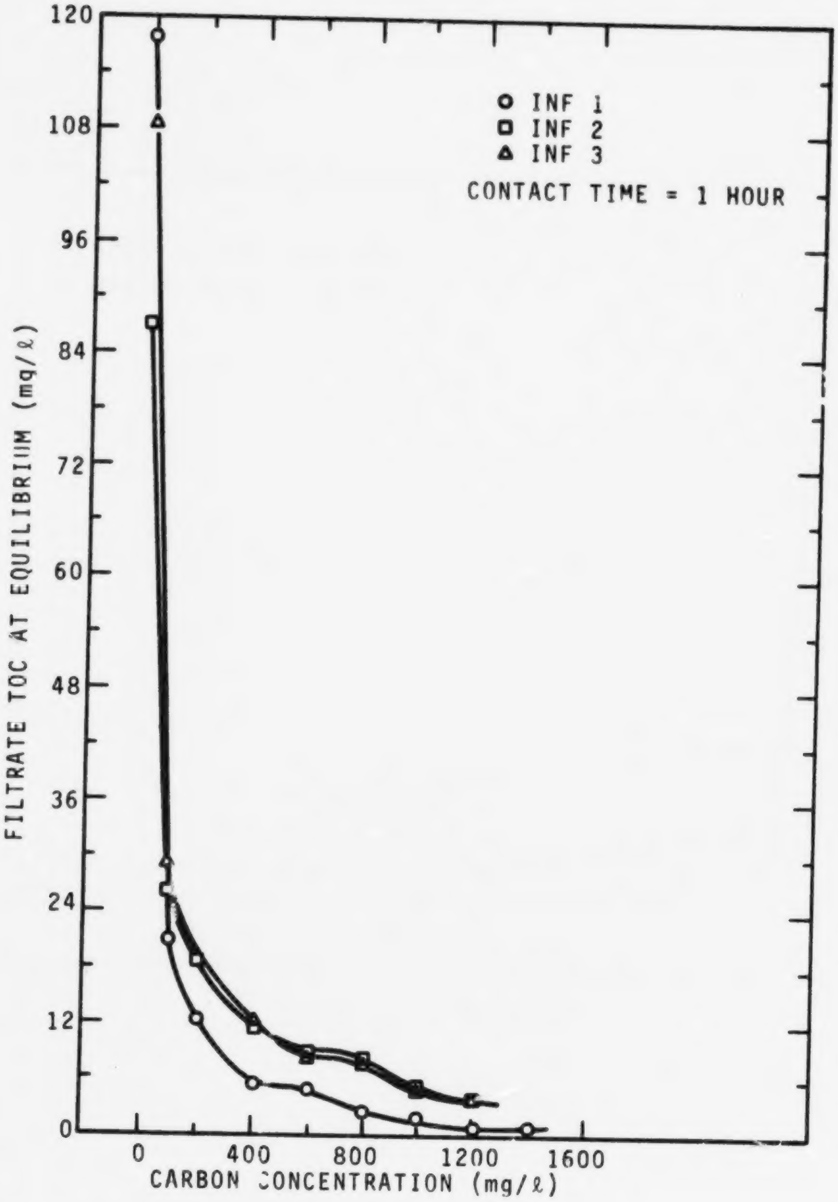


FIGURE A-3. EFFECT OF CARBON CONCENTRATION ON EQUILIBRIUM TOC

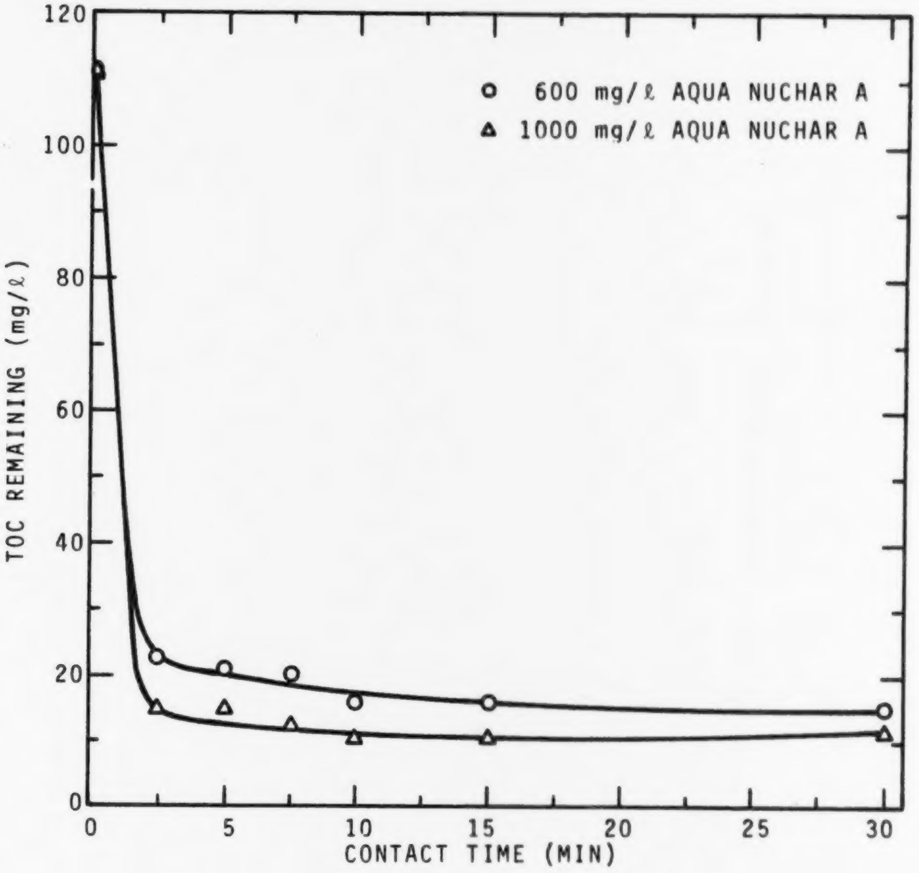


FIGURE A-4. EFFECT OF CONTACT TIME ON TOC REMOVAL

TABLE A-2

COMPARISON OF VARIOUS CARBONS - CONTACT TESTS

Sample	Sewage A TOC (mg/l) 1 hr contact	Sewage A TOC (mg/l) 21 hr contact	Sewage B TOC (mg/l) 1 hr contact	Bulk Cost (¢/#)
Nuchar CEEN	7	7	7.5	14
Darco S51	8.5	12	14.5	13
Nuchar WAN	8.5	9	9.5	10.5
Nuchar C190A	9	7	10.5	15.5
Nuchar C115N	10	10.5	--	15.5
Nuchar C115A	10	9.5	12.5	13.5
Nuchar Aqua	10.5	7	10.5	9
Nuchar C190N	11	12	--	15.5
Pittsburgh GW	11.5	7	10.5	15.5
Nuchar CEEA	13.5	8	--	14
Norit FQA	15	9.5	--	12.5
Darco GFP	16	10	--	10.5
Whitco 517	16.5	11	--	--
Darco KB	16.5	11	--	29
Norit F	17	12	--	11.5

Sewage A Soluble TOC = 35.5 mg/l

Sewage B Soluble TOC = 47.5 mg/l

Carbon Dose = 1000 mg/l

added after 5 minutes contact time and 10 mg/l of Magnifloc 985 N added after an additional 5 minutes. Samples were then flocculated, allowed to settle, and the unfiltered supernatant was analyzed for organic carbon as before. Results for two different sewage samples are given in Table A-3, together with several qualitative observations on wettability and floc characteristics.

Based on these findings, the decision was made to continue using Aqua Nuchar A since it appeared to offer the best benefit/cost ratio.

BENTONITE PROCESS DEVELOPMENT

Preliminary investigations prior to the start of the project indicated that bentonite clay, in conjunction with a polyelectrolyte, could effectively coagulate powdered carbon. Based on these preproject findings, Magnifloc 985 N, a high molecular weight, nonionic, polyacrylamide was selected for use in the early work.

A series of jar tests was conducted to determine the effect of bentonite concentration on the flocculation-sedimentation characteristics of the system with the results given in Figure A-5. When no bentonite was added to the system, large quantities of carbon remained in suspension at the end of the five minute settling period. Although it is not obvious from Figure A-5, the flocculation-sedimentation characteristics of the system noticeably improved up to a bentonite concentration of 300 mg/l. However, the five minute settling period was sufficient to effect good phase separation at a bentonite dose of 100 mg/l. This result was also observed when the polyelectrolyte dose was reduced to 5 mg/l. Simultaneous addition of bentonite and carbon to the system had no detectable effect on COD removal or flocculation. The pH of the system was varied from 5.5-8.1 and no significant change in system performance was observed. Turbidity of the settled effluent consistently ranged from 5-13 JTU. Upon filtration of these effluent samples, the residue on the membrane filter appeared to be clay rather than carbon.

These promising results prompted the initiation of an investigation of the effectiveness of the process in a continuous flow system. Table A-4 summarizes the data of five runs with the tube settler system. Carbon, bentonite and polyelectrolyte concentrations were set at 1000 mg/l, 300 mg/l, and 10 mg/l, respectively, in the initial runs to study the effect of variable flow rates. It was realized that these concentrations represented an excess of polyelectrolyte and probably bentonite as well.

It appeared that the bentonite dose could be reduced to 100-200 mg/l. In general, the bentonite process seemed to produce

TABLE A-3

COMPARISON OF VARIOUS CARBONS - JAR TESTS

Sample	TOC (mg/l)	TOC (mg/l)	Floc	Wettability
Whitco 517	9.5	14.5	Good	Good
Pittsburgh GW	9	20.5	Good	Average
Darco S51	11.5	16.5	Good	Good
Nuchar CEEN	12	35.5	Fair	Average
Nuchar Aqua	15.5	32.5	Good	Average
Nuchar WAN	11.5	17.5	Fairly Good	Average
Influent	47.5	75.5	--	--

Carbon Dose = 1000 mg/l

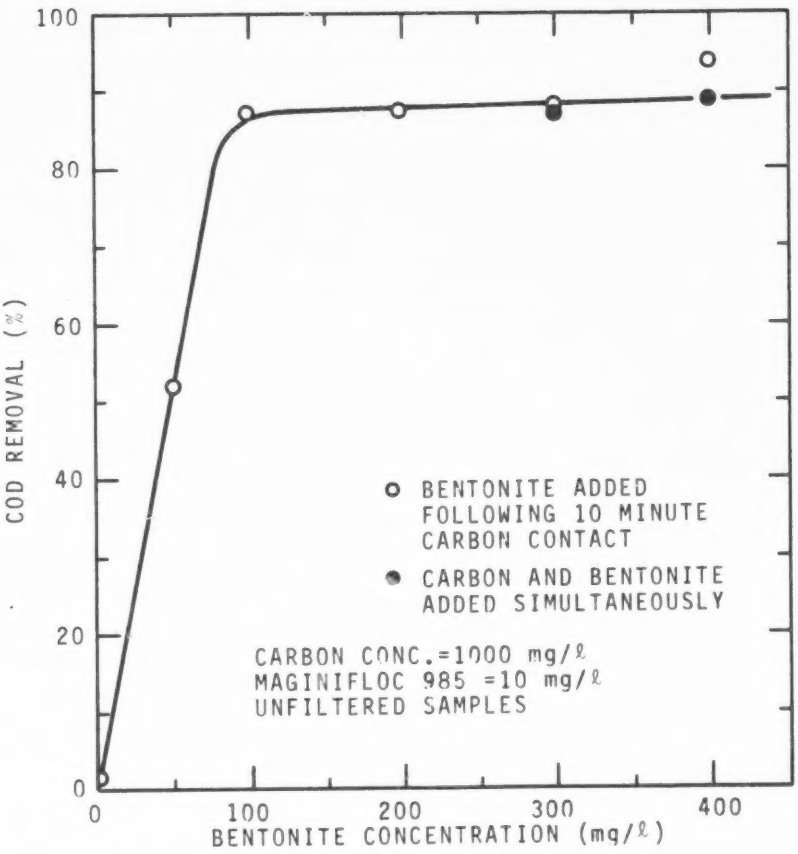


FIGURE A-5. EFFECT OF BENTONITE CONCENTRATION ON EFFLUENT QUALITY

TABLE A-4

BENCH SCALE SYSTEM OPERATIONAL DATA - TUBE SETTLER

Date	Influent COD (mg/l)	Influent S.S. (mg/l)	Flow Rate* (ml/min)	Carbon Conc. (mg/l)	Bentonite Conc. (mg/l)	Polyelectrolyte Conc. (mg/l)	Effluent S.S. (mg/l)	Effluent COD mg/l)	COD Removal (%)
8/25/69	84	71	195	1000	300	10	18	18	66
			195	1000	300	10	20	12	77
			100	1000	300	10	18	12	77
			100	1000	300	10	16	11	79
			48	1000	300	10	18	13	75
			48	1000	300	10	14	14	73
8/26/69	169	195	100	1000	300	10	44	46	73
			150	1000	300	10	18	38	77
			200	1000	300	10	50	56	67
			200	1000	300	10	50	42	75
			285	1000	300	10	45	46	73
			285	1000	300	6.7	30	46	73
8/27/69	184	134	300	1000	300	0.5	290	96	48
			300	1000	300	2.5	57	37	80
			300	1000	300	5.0	35	20	89
			300	1000	300	7.5	43	23	88
			100	1000	300	0.75	51	18	90
			100	1000	300	3.75	43	17	90
			100	1000	300	7.5	35	11	94
8/28/69	202	192	200	1000	0	10	117	174	14
			200	1000	50	10	51	70	65
			200	1000	100	10	51	49	76
			200	1000	150	10	44	57	72
			200	1000	200	10	26	45	78
			200	1000	300	10	28	28	86
8/29/69	400	239	200	1000	300	5	13	31	92
			200	1000	100	5	11	42	89
			300	1000	100	5	--	24	94

*Flow rates are listed in the order in which they were varied during a particular run. A flow rate of 100 ml/minute represents a loading rate of 4.84 gpm/ft^2 of tube surface.

a higher quality effluent in the continuous flow system than in the jar tests. Some further increase in flow rate may have been possible, but it was believed that the 300 ml/min flow was near the limit of the system without carbon carryover. This limitation was due to the sizing of the tube settler. The one inch diameter tube settler was a standard laboratory model purchased from Neptune MicroFloc Inc. At a system flow rate of 100 ml/min, the throughput rate of the tube settler was 4.84 gpm/ft^2.

An additional six runs were conducted with an upflow clarifier system. Flow rates were varied from 300-1500 ml/min, giving a range of system detention time from 62-12 minutes. Chemical doses were held constant at 300 mg/l bentonite, 1000 mg/l carbon, and 10 mg/l Magnifloc 985 throughout the runs. Results of these runs are summarized in Table A-5. Turbidity of the effluent ranged from 3.1 JTU at a flow rate of 300 ml/min, to 6.2 JTU at a flow rate of 1500 ml/min. As described later in this section, carbon-bentonite sludges were regenerated by Battelle-Columbus and by FMC Corporation. Jar test evaluations of the regenerated products revealed that the coagulating ability of the bentonite was destroyed to a considerable degree in the regeneration process. Apparently, thermal treatment causes the bentonite structure to collapse and this alteration renders it inoperable as a coagulant.

It was found necessary to add a full 300 mg/l of fresh bentonite to the regenerated carbon-bentonite mixtures in order to achieve good coagulation.

Even with the addition of new bentonite, the effluent had poor turbidity characteristics in comparison to the effluent produced using virgin carbon and bentonite. It is postulated that this was caused by the colloidal suspension of spent bentonite ash. Good clarification requires the addition of other flocculant aids.

A screening study was conducted in an attempt to find a suitable substitute for bentonite. Materials which were investigated and rejected include aluminum silicate, synthetic zeolite, diatomaceous earth, powdered silica, and asbestos.

Bentonite does not appear to offer much promise if thermal regeneration is to be utilized. It would probably be possible to recycle the carbon-bentonite mixture several times. However, buildup of the inorganic content will be severe, and frequent wasting of large quantities of carbon-bentonite would probably be required.

TABLE A-5

UPFLOW CLARIFIER OPERATING DATA

Flow Rate (ml/min)	Overflow Rate (gpm/ft^2)	Number of runs	Influent COD (mg/l)		Effluent COD (mg/l)		COD Removal %	
			Range	Avg	Range	Avg	Range	Avg
300	0.189	5	213-259	206	7-33	17	85-94	92
350	0.220	1	---	247	10-16	13	93-96	95
600	0.378	5	213-259	209	9-46	19	82-96	91
700	0.441	1	---	247	41-45	43	82-84	83
1500	0.945	3	213-259	196	22-38	28	81-87	84

ALUM PROCESS PRELIMINARY INVESTIGATIONS

Magnifloc 985 N was used throughout these initial investigations as was a carbon dose of 1000 mg/l. The alum [$Al_2(SO_4)_3 \cdot 18H_2O$] dose was varied in a series of jar tests. From inspection of the data of Figure A-6 it is apparent that adequate turbidity removal was achieved at an alum dose of 150 mg/l. However, objectionable quantities of powdered carbon remained in the effluent and good flocculation was not achieved until the alum dose had been increased to 350 mg/l. Additional jar tests at this alum concentration and at polyelectrolyte concentrations of 5-10 mg/l indicated that COD removals of >90% could be obtained consistently. It was observed that coagulation was impaired in some instances if alum and carbon were added simultaneously. A carbon contact time of at least five minutes prior to alum addition was required in order to insure consistently good floc formation.

Bench scale experiments with the alum process were then conducted. As indicated by the jar tests, a definite carbon contact time of at least five minutes was required before addition of the alum for coagulation to proceed normally. Data from runs with the upflow clarifier and the tube settler are presented in Tables A-6 and A-7.

In the first two of the runs with the tube settler, numerous mechanical difficulties with pumps, mixers, etc., arose. Due to the low flow rates employed, the system was slow to reach equilibrium. Therefore, the data reported for these first two runs does not represent optimum system performance but does indicate that even during minor upsets, a reasonable degree of treatment can be achieved. Tube settler performance was similar to that observed for the bentonite system: settling occurred primarily in the inlet chamber. The floc formed in this process was not as dense nor as tough as that formed with bentonite. Therefore, it was necessary to exercise greater care to prevent breakup of the floc and redispersion of the carbon after polyelectrolyte addition.

CARBON REGENERATION

An arrangement was made with Battelle-Columbus (BCL) and with FMC Corporation to regenerate a number of samples in their respective laboratory carbon regeneration systems. The initial carbon-bentonite sludge sample sent to FMC was generated in the laboratory bench scale unit. All of the sludge samples sent to BCL and the second set of FMC samples were generated by treating a larger quantity of sewage on a batch basis. Each set of sludge samples was generated by treating six hundred gallons of sewage in batches of 50 gallons. Half was treated using the bentonite process and half by the alum process. After initial separation, the sludge was allowed to

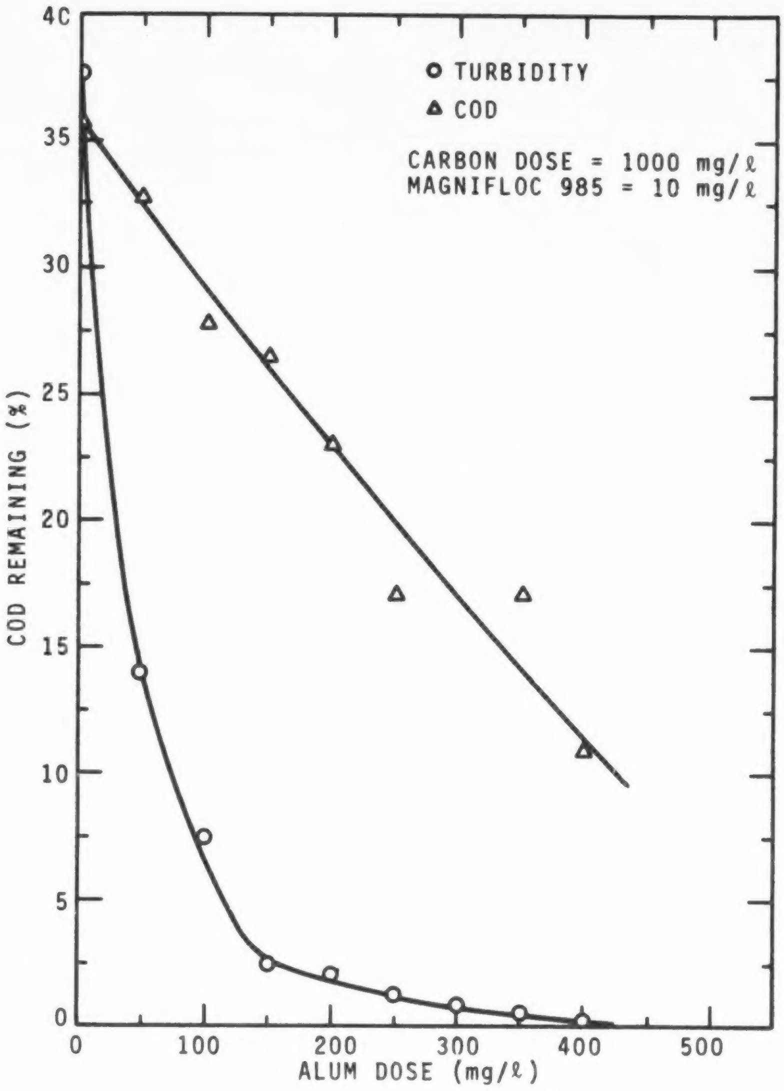


FIGURE A-6. EFFECT OF ALUM DOSE ON COD AND TURBIDITY REMOVAL

TABLE A-6

UPFLOW CLARIFIER SYSTEM - ALUM PROCESS PERFORMANCE

Influent COD (mg/1)	Flow Rate (ml/min)	Overflow Rate (gpm/ft^2)	Alum* Conc. (mg/1)	Polyelectrolyte Concentration (mg/1)	Effluent			COD Removal %
					SS (mg/1)	Turbidity (JTU)	COD (mg/1)	
180	600	0.378	400	10	13	2	12	93.4
	600	0.378	350	10	19	1.5	8	95.6
	300	0.189	350	10	13	111	4	97.5
	300	0.189	350	5	16	1	13	93
324	600	0.378	350	4	36	5.1	38	88
	300	0.189	350	5	18	2.5	26	92

*Alum - $Al_2(SO_4)_3.18H_2O$

Carbon Dose = 1000 mg/1

TABLE A-7

TUBE SETTLER SYSTEM - ALUM PROCESS

Influent COD (mg/1)	Influent TOC (mg/1)	Flow Rate (ml/min)	Tube Loading Rate (gpm/ft^2)	Effluent S.S. (mg/1)	Effluent Turbidity (JTU)	Effluent COD (mg/1)	Effluent TOC (mg/1)	Removal COD (%)	Removal TOC (%)
280	46	150	7.26	14	2.1	70	8.0	76	81.5
		200	9.68	9	1.6	36	8	87	82.6
188	73	150	7.26	11	3.0	28	4.5	85	93.8
		200	9.68	16	2.5	53	-	72	--
>800	86	150	7.26	20	2.0	53	11.5	>93	86.6
		250	12.10	9	1.5	57	-	>93	--
186	66	250	12.10	13	3.0	32	9	83	86.3
		300	14.52	13	4.0	19	21	90	46

Carbon dose - 1000 mg/1
Alum dose = 350 mg/1
Polelectrolyte dose = 10 mg/1

concentrate for several hours, the supernatant liquid was poured off, and this procedure was repeated a second time. In most cases, the dewatered sludge was oven dried before shipment. Physical losses in handling these small quantities of carbon were significant in both cases and therefore it is difficult to estimate the processing losses involved in either system. In fact, these handling losses were so high that large quantities of makeup carbon had to be added after each regeneration cycle. Therefore, an exact picture of several cycles of use and reuse could not be obtained.

Carbon was followed through three regeneration cycles for the Battelle-Columbus process. The carbon composition of the sludge regenerated in each cycle was as follows:

First Cycle -	Bentonite Process	100% Virgin carbon
	Alum Process	100% Virgin carbon
Second Cycle-	Bentonite Process	75% First cycle regenerated carbon 25% Virgin carbon
	Alum Process	50% First cycle regenerated carbon 50% Virgin carbon
Third Cycle -	Bentonite Process	66% Second cycle regenerated carbon
	Alum Process	55% Second cycle regenerated carbon 45% Virgin carbon

Samples of the various regenerated carbon mixtures were analyzed for carbon, water, and ash content with the results given in Table A-8. It should be noted that the ash content reading includes the alum and bentonite residue except in the case of the acid extracted carbon. These data show how the bentonite content of the sludge from the bentonite process increases with each cycle. An ash content of 44 percent was measured after the third regeneration. On the other hand, the composition of the acid extracted carbon-alum mixture is comparable for the second and third cycles. Definite conclusions concerning physical losses and ash buildup in the alum process could not be drawn on the basis of the laboratory studies. Carbon contact tests were employed to determine the capacity recovery of the carbon after regeneration. The aluminum-containing mixtures were slurried overnight at a pH of 0.5 to dissolve all soluble aluminum. The dried powders, regenerated bentonite-carbon, and new Aqua Nuchar were then measured out at 0.5, 0.75, 1.0 and 1.5 gm/liter for contact tests. Samples were shaken for one hour, filtered through

TABLE A-8

ANALYSIS OF REGENERATED CARBON MIXTURES

	Carbon Content (%)	Water Content (%)	Ash Content (%)
Virgin Aqua Nuchar			
1	84.1	9.0	2.4
2	86.6	4.5	2.3
3	83.6	10.8	1.7
BCLA			
1st Cycle	81.6	6.8	12.5
2nd Cycle	75.2	7.2	17.5
3rd Cycle	73.0	6.1	19.8
ABCLA			
1st Cycle	--	--	--
2nd Cycle	68.3	13.5	8.2
3rd Cycle	67.6	16.2	7.4
BCLB			
1st Cycle	69.7	5.7	25.2
2nd Cycle	60.0	1.8	37.6
3rd Cycle	53.5	4.5	44.2
FMCA			
1st Cycle	66.6	2.7	29.3
AFMCA			
1st Cycle	60.7	11.7	22.4
FMCB			
Batch Scale	65.1	3.6	32.1
1st Cycle	81.6	2.3	15.5

BCLB - Regenerated carbon-bentonite mixture - Battelle-Columbus process
BCLA - Regenerated carbon-alum mixture - Battelle-Columbus process
ABCLA - Acid extracted regenerated carbon-alum mixture - Battelle-Columbus process
FMCB - Regenerated carbon-bentonite mixture - FMC process
FMCA - Regenerated carbon-alum mixture - FMC process
AFMCA - Acid extracted regenerated carbon-alum mixture - FMC process

0.45 μ membrane filters, and analyzed for organic carbon. The data obtained are presented in Figures A-7, A-8, and A-9. These data indicate that capacity recovery lies somewhere between 90-100 percent.

A series of jar tests was run on sewage using virgin and the various regenerated carbons. Analyses performed on the settled supernatants are presented in Table A-9. The nutrient results were predictable except for the apparent removal of NO_3^- which cannot be explained. Acid treatment of the recovered carbon-alum mixture produces a carbon which is apparently as good as or better than the fresh product.

ALUM RECOVERY

An investigation was initiated to study the possibilities of aluminum recovery from the regenerated carbon-alum mixture. It is known that aluminum hydroxide goes through the conversion

$$Al(OH)_3 \xrightarrow{500°C} \gamma\text{-}Al_2O_3 \xrightarrow{1000°C} \alpha\text{-}Al_2O_3$$

The γ-oxide readily dissolves in H_2SO_4 to reform Al ions while the α-oxide is insoluble at reasonable acid levels. Since carbon regeneration takes place below 1000°C, the majority of the aluminum should be recoverable. Two gram samples of regenerated sludge were slurried and acidified over a range of pH values and the solution phase was then analyzed for aluminum content colorimetrically. This procedure was followed for both the first cycle and third cycle BCL regenerated carbon-aluminum mixtures. Results of these experiments are summarized in Figures A-10 and A-11. Recovery of approximately 86 percent of the aluminum at a pH of 1.75 was observed with the first cycle mixture. Aluminum recovery approached 100 percent for the third cycle case. The acid requirement was virtually identical in both cases. At this time, alum recovery appeared highly feasible.

Reuse of this recovered alum is discussed in the section on the alum process optimization.

A similar line of investigation was pursued for a $Fe_2(SO_4)_3$ coagulant. However, a red powder, believed to be Fe_2O_3 (which should form at 200°C), formed in the thermal regeneration step. This iron oxide was very acid resistant and a good dissolution to recover ferric ion could not be achieved at reasonable acid levels. It was concluded that the recovery of Fe_2SO_4, in this manner, was not feasible.

POLYELECTROLYTE SCREENING STUDY

Jar tests were run on a spectrum of commercial polyelectrolytes to identify those best suited for the operation.

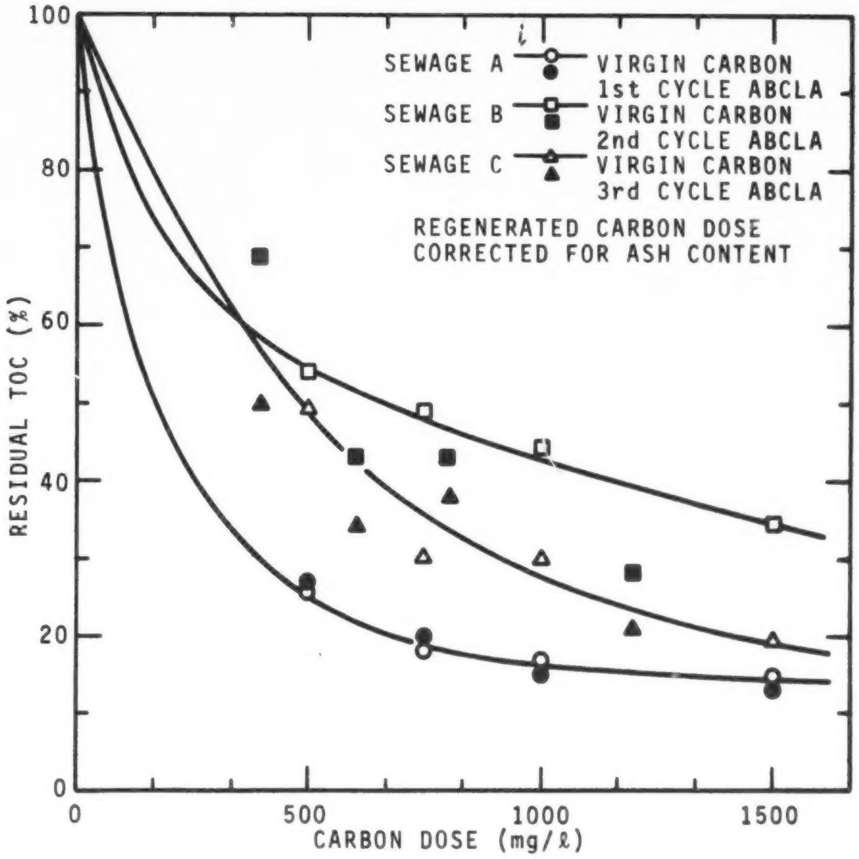


FIGURE A-7. CAPACITY RECOVERY OF BATTELLE-COLUMBUS REGENERATED CARBON-ALUM PROCESS

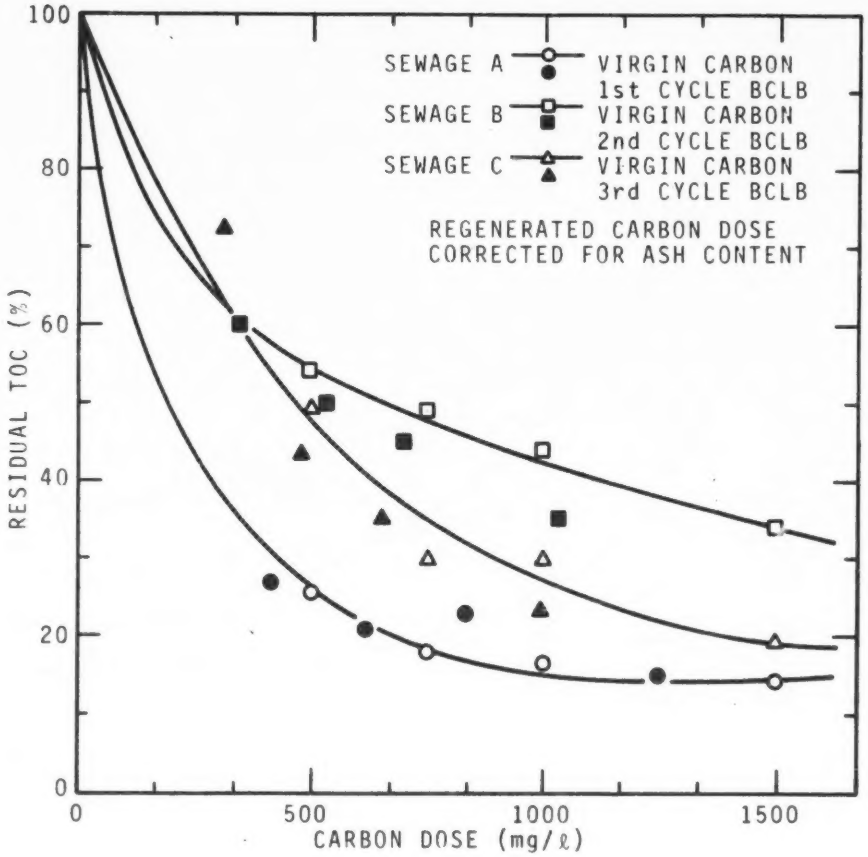


FIGURE A-8. CAPACITY RECOVERY OF BATTELLE-COLUMBUS REGENERATED CARBON-BENTONITE PROCESS

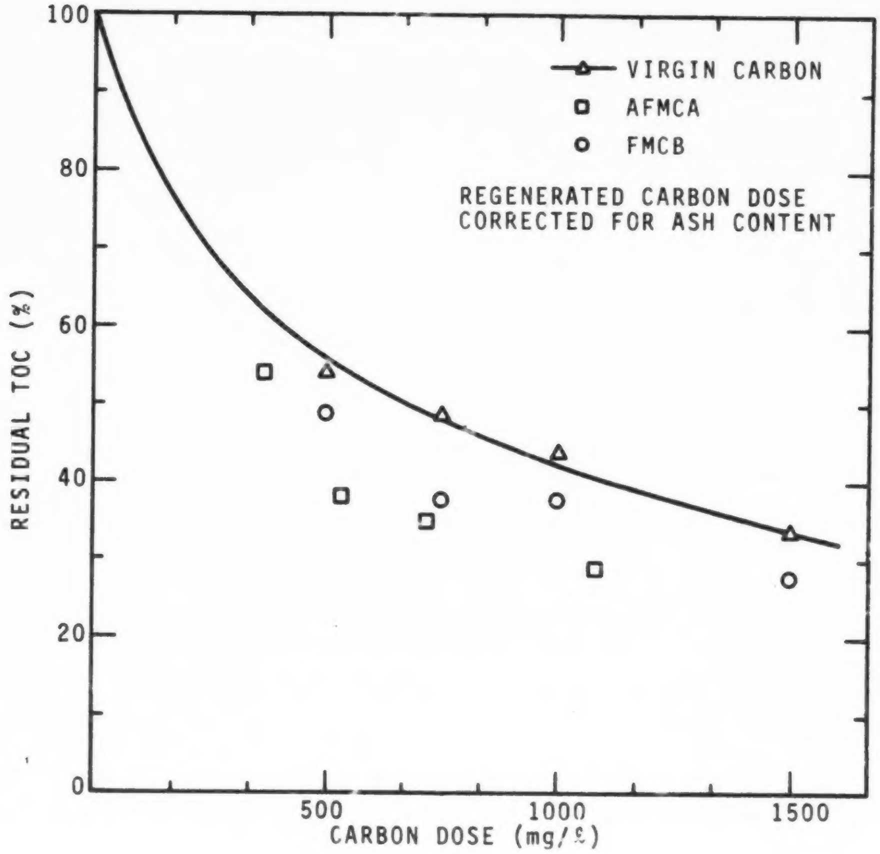


FIGURE A-9. CAPACITY RECOVERY OF FMC REGENERATED CARBONS

TABLE A-9

JAR TEST RESULTS WITH REGENERATED CARBONS

	NO_3-N (mg/l)	NH_3-N (mg/l)	PO_4 (mg/l)	TOC (mg/l)
Influent	2.2	31	31.2	41
VC + Alum	0.22	28	3	9
VC + bentonite	<0.1	27	26.8	11.5
BCLB + 150 mg/l bentonite	<0.1	26	28.8	13.5
BCLB + 300 mg/l bentonite	<0.1	27	28.8	16.5
FMCB + 150 mg/l bentonite	<0.1	27	26.8	12.5
FMCB + 300 mg/l bentonite	<0.1	26	28.8	13
ABCLA + recovered alum	<0.1	26	25.4	8.5
ABCLA + virgin alum	<0.1	26	0.8	9.5

VC - Virgin carbon
BCLB - Regenerated carbon-bentonite mixture - Battelle-Columbus process
BCLA - Regenerated carbon-alum mixture - Battelle-Columbus process
ABCLA - Acid treated regenerated carbon-alum mixture - Battelle-Columbus process
FMCB - Regenerated carbon-bentonite mixture - FMC process
Carbon Dose = 1000 mg/l

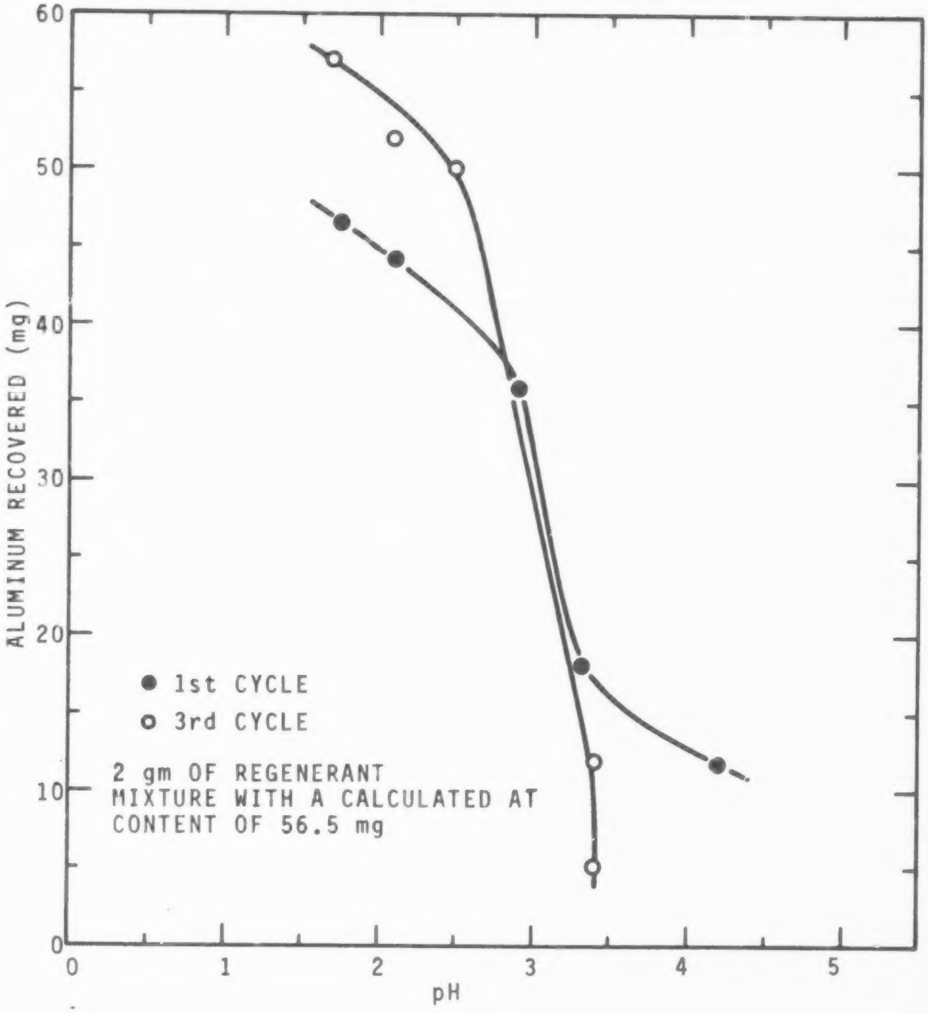


FIGURE A-10. EFFECT OF pH ON ALUMINUM RECOVERY

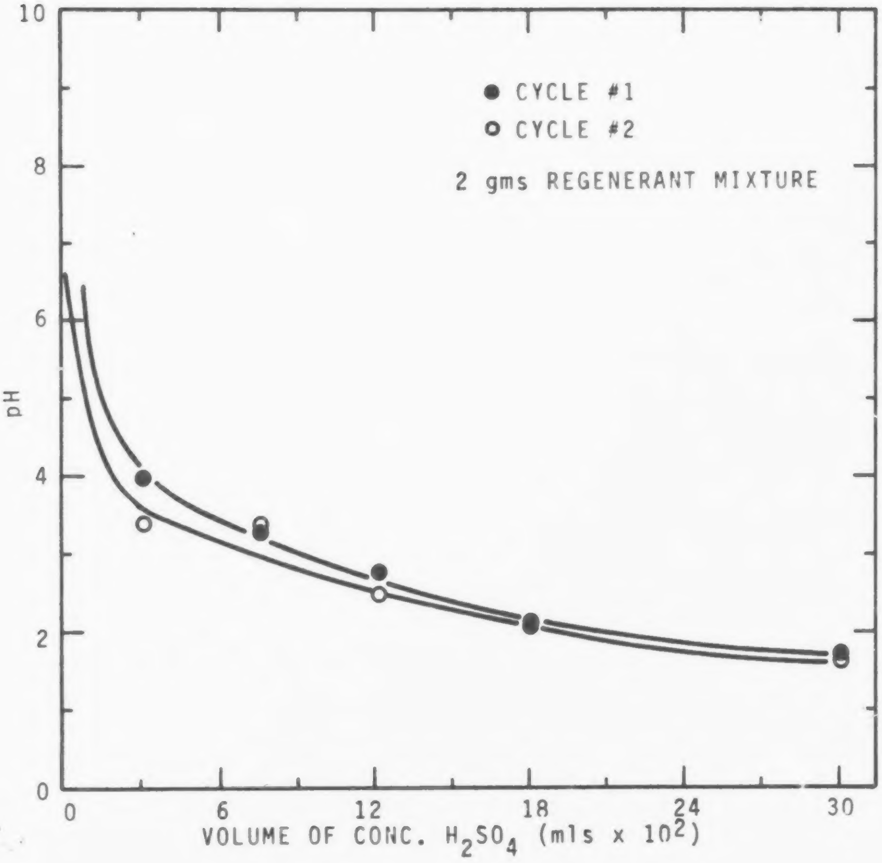


FIGURE A-11. ACID REQUIREMENT VERSUS pH-BCL CARBON-ALUM MIXTURE

TABLE A-10

FLOCCULATION PERFORMANCE OF VARIOUS POLYELECTROLYTES

Polyelectrolyte @ 10 mg/l	Performance in Alum System	Performance in Bentonite System
Nalco 600	Negligible	Negligible
Nalco 672	Good	Good
Magnifloc 837 A*	Good	--
Magnifloc 905 N	Fair-Good	Good
Atlas 105-659	Good	Fair
Atlas 300-400	Good	Good
Polyhall M-19	Fair	Fair
Purifloc N-17	Fair	Fair
Purifloc A-23	Very Good	Negligible
Purifloc C-23	Negligible	Negligible
Zetafloc WA	Poor	Negligible

*This is a commercial grade of Magnifloc 985 N

TABLE A-11

EFFECT OF DOSE ON POLYELECTROLYTE PERFORMANCE - ALUM SYSTEM

	Performance				
Dosage (mg/l)	1	2.1	5	7.5	10
Polyelectrolyte					
Nalco 672	Poor	Poor-Fair	Good	Good	Good
Atlas 300-400	Fair	Good	Very Good	Very Good	Very Good
Purifloc A-23	Fair	Very Good	Very Good	Very Good	Very Good
Magnifloc 837 A	Poor	Fair	Fair	Good	Good

Qualitative observations on the performance of these polyelectrolytes appear in Table A-10. As a result of this series, four brands were selected for more extensive testing in which doses were varied from 1-10 mg/l. Flocculating characteristics observed in these tests are given in Table A-11.

ALUM PROCESS OPTIMIZATION

It was decided to re-examine earlier results, which indicated that a definite carbon contact time was required before alum addition. This point was critical, since the process would be highly simplified if it was not necessary to separate the reclaimed alum from the carbon before reuse. Jar tests were devised whereby the recovered alum was added simultaneously with the carbon. After a five minute contact time, caustic was added to raise the pH and then, after an additional five minutes, polyelectrolyte was added. Flocculation proceeded normally as long as the caustic addition was regulated to achieve the desired effluent pH of approximately 7. This indicated that the recovered alum would not have to be separated from the carbon as thought earlier. Consequently, similar tests were run on daily sewage samples for a period of two weeks in conjunction with jar tests in which fresh alum was added simultaneously with the carbon. The recovered alum solutions exhibited good flocculation every time while several samples in which fresh alum was employed would not flocculate. This result suggested that the carbon could remove the interfering substance if the solution was maintained in an acidified state for the first few minutes of contact. All subsequent observations reinforced this conclusion.

In order to further investigate the feasibility of using reclaimed alum, the bench scale system was set up with a chemical addition line located downstream from the carbon contact tank and pH probe located slightly further downstream. Throughout all of the runs, a lime slurry was pumped continuously in sufficient quantity to maintain the pH in the range of 6.5-7.0 at the downstream point. In the initial run, a slurry of fresh carbon and reclaimed alum was prepared and added in the same manner as the carbon slurry in previous runs. Doses were 1000 mg/l C, 10 mg/l Purifloc A-23 and 350 mg/l alum. A TOC removal of 90 percent with a residual TOC of 9 mg/l was observed. Subsequent operation with a slurry of FMC regenerated carbon-reclaimed alum resulted in an effluent with a residual TOC of 8.5 mg/l.

Additional bench scale experiments were conducted to study the dose requirements of the polyelectrolytes which showed promise in the beaker tests. FMC regenerated carbon and reclaimed alum were employed in these runs with the results given in Table A-12. Effluents of high quality were produced consistently in these runs. This process employing regenerated carbon and reclaimed

TABLE A-12

EFFECT OF POLYELECTROLYTE DOSE ON BENCH SCALE PERFORMANCE

Influent TOC (mg/l)	Polyelectrolyte	Dose (mb/l)	Effluent TOC (mg/l)	TOC Removal (%)
129	Magnifloc 837-A	10	16	87.7
		5	14.5	88.9
		2.5	14	89.2
	Atlas 300-400	5	12	90.8
		2.5	10.5	91.9
	Purifloc A-23	2.5	10.5	91.9
76	Nalco 672	2.5	0.0	>99
		5.0	0.0	>99
		10.0	4.0	95
	Purifloc A-23	1.0	0.0	>99
		1.25	0.0	>99
		2.0	2.5	97
		2.5	0.0	>99
	Atlas 300-400	1.25	0.0	>99
		2.5	0.0	>99

alum with pH control proved to be highly reliable in the continuous flow laboratory system.

Based on these results, it was concluded that the Atlas 300-400 and Purifloc A-23 were the two polyelectrolytes best suited for alum flocculation.

Data obtained in the carbon contact tests suggested that the carbon dose could be reduced substantially below 1000 mg/l. Subsequent jar tests confirmed that there was little difference in effluent quality if the carbon dose was reduced from 1000 mg/l to 600 mg/l. Consequently, the bench scale system was run at 600 mg/l carbon. Earlier jar tests also indicated that with the Purifloc A-23, the alum dose could be reduced to as low as 150 mg/l. The two new doses were checked simultaneously at a Purifloc A-23 dose of 2.5 mg/l, with the results given below:

	Alum Dose (mg/l)	Influent TOC (mg/l)	Effluent TOC (mg/l)	Removal (%)
Inf. A-016 g/l ABCLA carbon	150	105	3	97
Inf. B-016 g/l Aqua Nuchar	200	88	11	88
Inf. A-016 ABCLA carbon	250	105	4	96

A small amount of carbon carryover was evident at the low alum dose, but disappeared when the alum dose was increased to 200 mg/l. It was concluded that satisfactory process performance could be achieved with a carbon dose of 600 mg/l and an alum dose of 200 mg/l. Further reduction in the carbon dose may be possible with low TOC waste streams.

In order to investigate the effect of high solids and organic loading on process performance, a special influent was prepared by adding aged (60 days) primary sludge to Richland raw sewage. The resulting mixture contained 2680 mg/l total solids and 1400 mg/l TOC. This waste was then treated in the bench scale system with chemical doses at 600 mg/l Aqua Nuchar and 200 mg/l alum. Initially, the system was operated at a polyelectrolyte (Purifloc A-23) dose of 10 mg/l with a resulting residual TOC of 47 mg/l or 97 percent TOC removal. Effluent TOC declined after startup and subsequent operation at a Purifloc A-23 dose of 2.5 mg/l produced a product with a TOC residual of 17.5 mg/l, which represents 99 percent TOC removal. Throughout the course of the run, effluent turbidities never exceeded 1 JTU. These results indicate that the treatment process can easily handle waste streams with high solids contents.

The system, at the conclusion of the laboratory studies, had shown a high degree of stability with little or no upset at startup and rapid recovery from pH disturbances. Carbon carryover was unnoticeable, turbidity consistently less than 1 JTU, and TOC removals greater than 90 percent.

☆U.S. GOVERNMENT PRINTING OFFICE: 1973 514-153/199 1-3